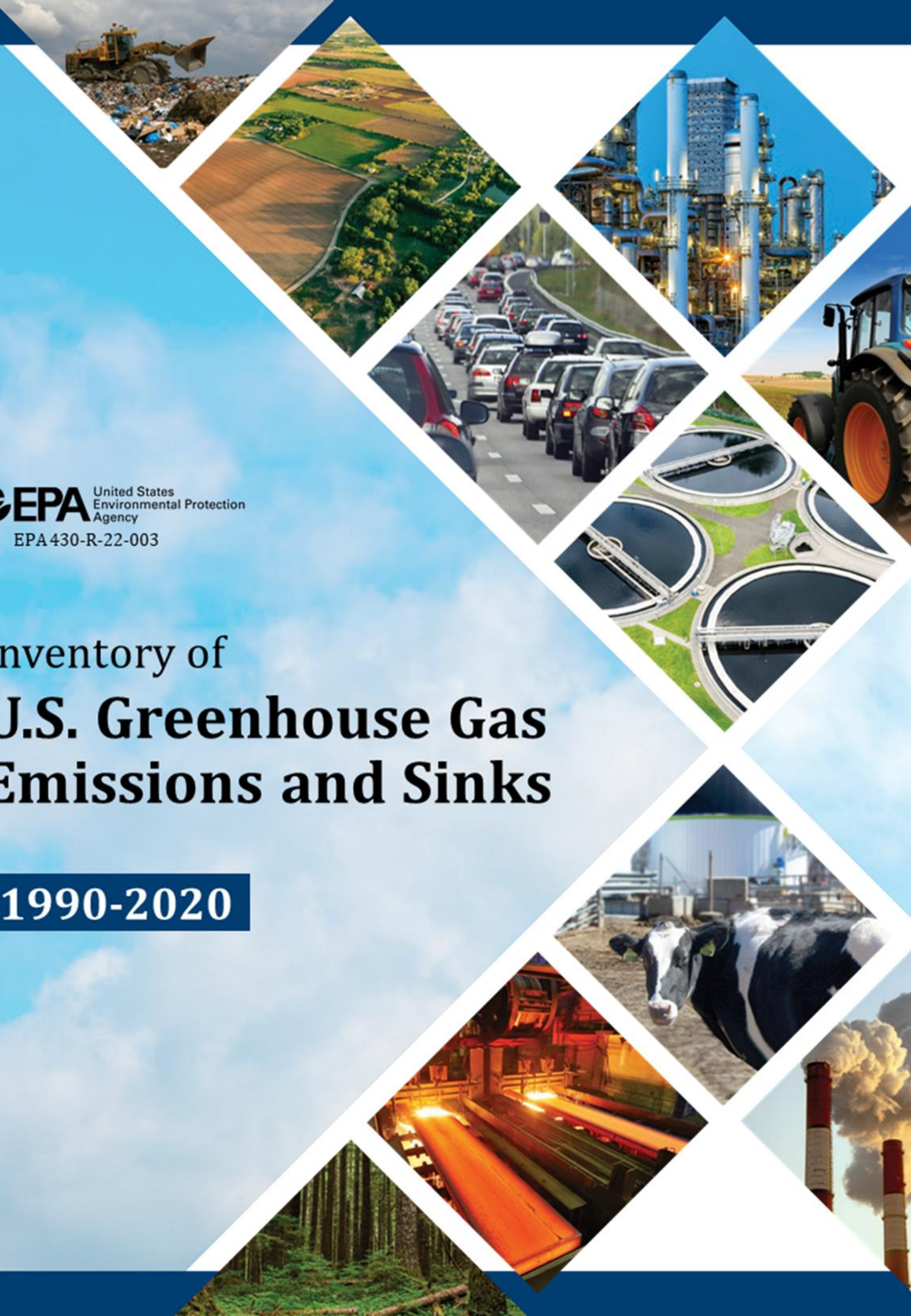

United States Environmental Protection Agency

EPA 430-R-22-003

Inventory of
U.S. Greenhouse Gas Emissions and Sinks

1990-2020

Front cover photo credit for cow and digester: Vanguard Renewables.

HOW TO OBTAIN COPIES

You can electronically download this document on the U.S. EPA's homepage at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

All data tables of this document for the full time series 1990 through 2020, inclusive, will be made available with the final report published by April 15, 2022 at the internet site mentioned above.

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FOR FURTHER INFORMATION

Contact Ms. Mausami Desai, Environmental Protection Agency, (202) 343-9381, desai.mausami@epa.gov,

or Mr. Vincent Camobreco, Environmental Protection Agency, (202) 564–9043, camobreco.vincent@epa.gov.

For more information regarding climate change and greenhouse gas emissions, see the EPA web site at https://www.epa.gov/ghgemissions.

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Preface

The United States Environmental Protection Agency (EPA) prepares the official U.S. Inventory of Greenhouse Gas Emissions and Sinks to fulfill annual existing commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Under UNFCCC Article 4 and decisions at the First, Second, Fifth and Nineteenth Conference of Parties, national inventories for UNFCCC Annex I parties should be provided to the UNFCCC Secretariat each year by April 15.

In an effort to engage the public and researchers across the country, the EPA has instituted an annual public review and comment process for this document. The availability of the draft document on the EPA Greenhouse Gas Emissions web site was announced via Federal Register Notice. The public comment period covered a 30-day period from February 15 through March 17, 2022, and comments received during the public review period were posted to the docket EPA-HQ-OAR-2022-0001. Comments received after the closure of the public comment period were accepted and will be considered for the next edition of this annual report. Responses to comments are typically posted to EPA's website 2-4 weeks following publication of the final report in April 2022.

Table of Contents

List of Tables, Figures, Boxes, and Equations

Tables

Figures

Boxes

Equations

Executive Summary

An emissions inventory that identifies and quantifies a country's anthropogenic[1] sources and sinks of greenhouse gases is essential for addressing climate change. This Inventory adheres to both (1) a comprehensive and detailed set of methodologies for estimating national sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change.

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2]

As a signatory to the UNFCCC, consistent with Article 4[3] and decisions at the First, Second, Fifth, and Nineteenth Conference of Parties,[4] the United States is committed to submitting a national inventory of anthropogenic sources and sinks of greenhouse gases to the UNFCCC by April 15 of each year. The United States views this report, in conjunction with Common Reporting Format (CRF) reporting tables that accompany this report, as an opportunity to fulfill this annual commitment under the UNFCCC.

This executive summary provides the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2020. The structure of this report is consistent with the UNFCCC guidelines for inventory reporting, as discussed in Box ES-1.[5]

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[1] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[2] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change. See http://unfccc.int.

[3] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12) and subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. Article 4 states "Parties to the Convention, by ratifying, shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…" See http://unfccc.int for more information.

[4] See UNFCCC decisions 3/CP.1, 9/CP.2, 3/CP.5, and 24/CP.19 at https://unfccc.int/documents.

[5] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Box ES-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the UNFCCC requirement under Article 4.1 and related decisions to develop and submit annual national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory does not preclude alternative examinations, but rather this Inventory presents emissions and removals in a common format consistent with how countries are to report inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP), which is complementary to the U.S. Inventory.[6] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers in 41 industrial categories.[7] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines*. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and sinks (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in the Inventory.

The GHGRP dataset provides not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., use of Subpart W data in compiling estimates for natural gas systems).

ES.1 Background Information

Greenhouse gases absorb infrared radiation, thereby trapping heat in the atmosphere and making the planet warmer. The most important greenhouse gases directly emitted by humans include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and several fluorine-containing halogenated substances (HFCs, PFCs, SF_6 and NF_3). Although CO_2, CH_4, and N_2O occur naturally in the atmosphere, human activities have changed their atmospheric

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[6] On October 30, 2009 the EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[7] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

concentrations. From the pre-industrial era (i.e., ending about 1750) to 2020, concentrations of these greenhouse gases have increased globally by 47.9, 168.4, and 23.3 percent, respectively (IPCC 2013; NOAA/ESRL 2022a, 2022b, 2022c). This annual report estimates the total national greenhouse gas emissions and removals associated with human activities across the United States.

Global Warming Potentials

The IPCC developed the global warming potential (GWP) concept to compare the ability of a greenhouse gas to trap heat in the atmosphere relative to another gas. The GWP of a greenhouse gas is defined as the ratio of the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram of the gas, relative to that of the reference gas CO_2 (IPCC 2013); therefore, GWP-weighted emissions are provided in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[8, 9] Estimates for all gases in this Executive Summary are presented in units of MMT CO_2 Eq. Emissions by gas in unweighted mass kilotons are provided in the Trends and sector chapters of this report and in the Common Reporting Format (CRF) tables that are also part of the submission to the UNFCCC.

UNFCCC reporting guidelines for national inventories require the use of 100-year GWP values from the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007) to ensure that national greenhouse gas inventories reported by all nations are comparable.[10] All estimates are provided throughout the report in both CO_2 equivalents and unweighted units. A comparison of emission estimates using the 100-year AR4 GWP values versus the *IPCC Fifth Assessment Report* (AR5) (IPCC 2013) and the *IPCC Sixth Assessment Report (AR6)* (IPCC 2021) GWP values can be found in Chapter 1 and, in more detail, in Annex 6.1 of this report. The GWP values used in this report are listed below in Table ES-1. The UNFCCC will require countries to shift to use AR5 100-year GWP values in 2024, when countries submit their first reports using updated reporting guidelines under the Paris Agreement.[11]

Table ES-1: Global Warming Potentials (100-Year Time Horizon) Used in this Report

Gas	GWP
CO_2	1
CH_4[a]	25
N_2O	298
HFCs	up to 14,800
PFCs	up to 12,200
SF_6	22,800
NF_3	17,200
Other Fluorinated Gases	See Annex 6

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to production of CO_2 is not included. See Annex 6 for additional information.

Source: IPCC (2007).

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[8] Carbon comprises 12/44 of carbon dioxide by weight.

[9] One million metric ton is equal to 10^{12} grams or one teragram.

[10] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

[11] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2020, total gross U.S. greenhouse gas emissions were 5,981.4 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq).[12] Total U.S. emissions have decreased by 7.3 percent from 1990 to 2020, down from a high of 15.7 percent above 1990 levels in 2007. Emissions decreased from 2019 to 2020 by 9.0 percent (590.4 MMT CO_2 Eq.). Net emissions (including sinks) were 5,222.4 MMT CO_2 Eq. in 2020. Overall, net emissions decreased 10.6 percent from 2019 to 2020 and decreased 21.4 percent from 2005 levels as shown in Table ES-2. The sharp decline in emissions from 2019 to 2020 is largely due to the impacts of the coronavirus (COVID-19) pandemic on travel and economic activity. However, the decline also reflects the combined impacts of long-term trends in many factors, including population, economic growth, energy markets, technological changes including energy efficiency, and the carbon intensity of energy fuel choices. Between 2019 and 2020, the decrease in total greenhouse gas emissions was driven largely by a 10.5 percent decrease in CO_2 emissions from fossil fuel combustion, including a 13.3 percent decrease in transportation sector emissions from less travel due to the COVID-19 pandemic and a 10.4 percent decrease in emissions in the electric power sector. The decrease in electric power sector emissions was due to a decrease in electricity demand of about 2.5 percent and also reflects the continued shift from coal to less carbon intensive natural gas and renewables.

Figure ES-1, Figure ES-2, and Figure ES-3 illustrate the overall trends in total U.S. emissions by gas, annual percent changes, and relative change since 1990 for each year of the time series, and Table ES-2 provides information on trends in gross U.S. greenhouse gas emissions and sinks for 1990 through 2020. Unless otherwise stated, all tables and figures provide total gross emissions and exclude the greenhouse gas fluxes from the Land Use, Land-Use Change, and Forestry (LULUCF) sector. For more information about the LULUCF sector see Section ES.3 Overview of Sector Emissions and Trends.

Table ES-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	5,122.5	6,137.6	5,251.8	5,211.0	5,376.7	5,259.1	4,715.7
CH_4[a]	780.8	697.5	657.6	663.8	671.1	668.8	650.4
N_2O[a]	450.5	453.3	449.2	444.6	457.7	456.8	426.1
HFCs	46.5	127.4	168.3	171.1	171.0	175.9	178.8
PFCs	24.3	6.7	4.4	4.2	4.8	4.6	4.4
SF_6	28.8	11.8	6.0	5.9	5.7	5.9	5.4
NF_3	+	0.5	0.6	0.6	0.6	0.6	0.6
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Emissions[a]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change/CO_2[b]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[c]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

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[12] The gross emissions total presented in this report for the United States excludes emissions and removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and removals from LULUCF.

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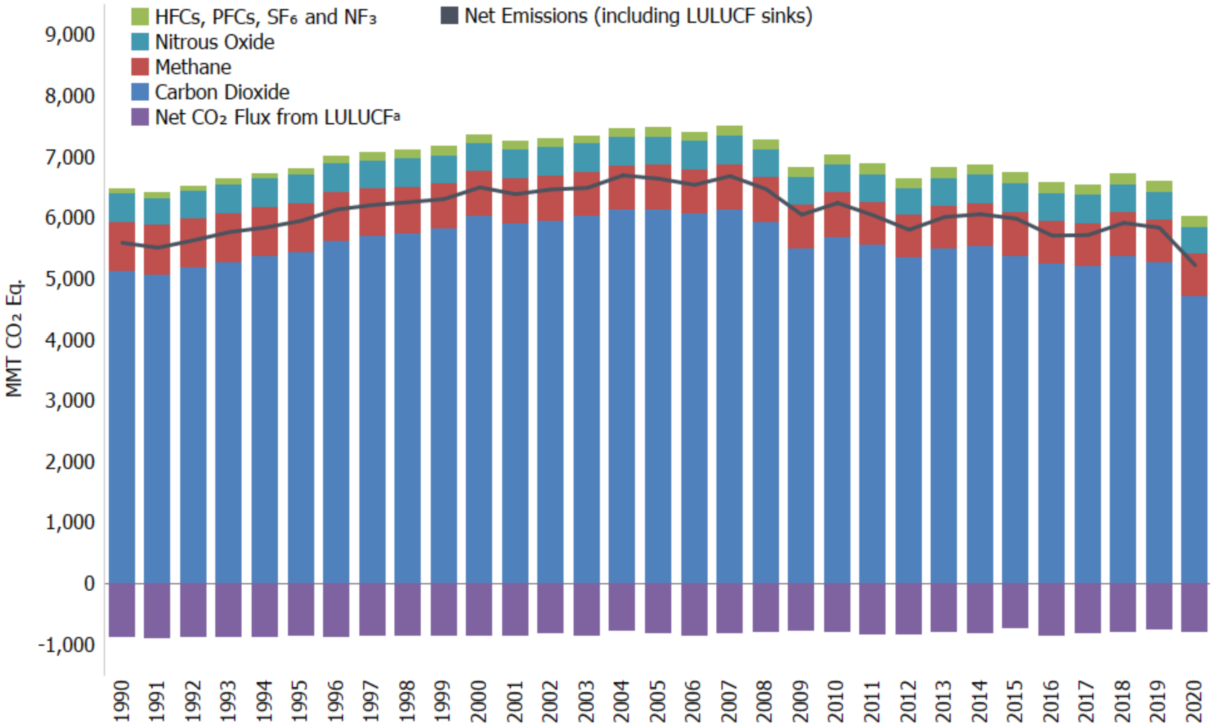
[b] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland*, Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[c] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net C stock changes.

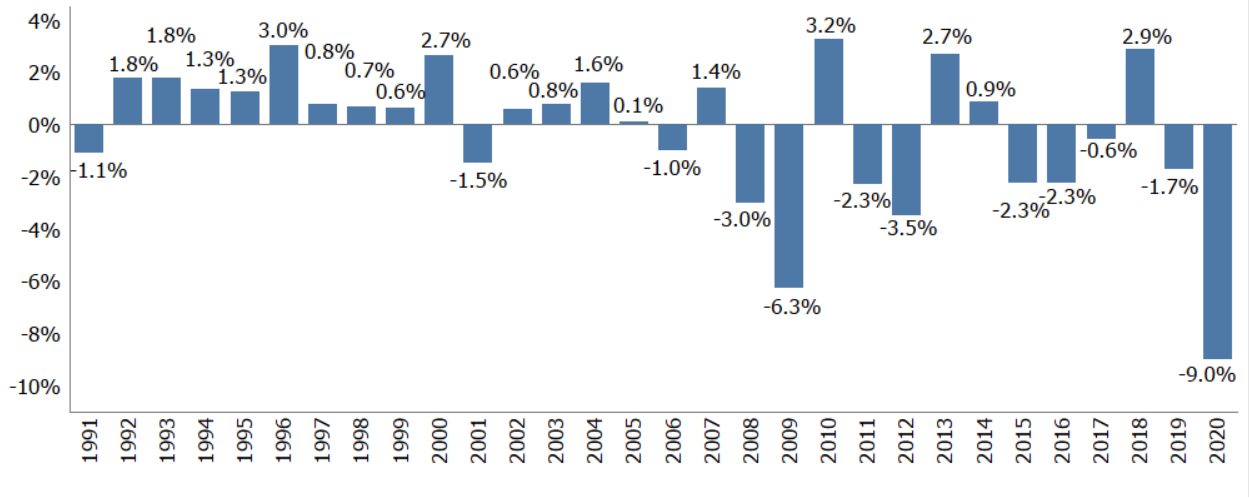
Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Figure ES-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Figure ES-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions and Sinks Relative to the Previous Year



Improvements and Recalculations Relative to the Previous Inventory

Each year, some emission and sink estimates in the Inventory are recalculated and revised to incorporate improved methods and/or data. The most common reason for recalculating U.S. greenhouse gas emission estimates is to update recent historical data. Changes in historical data are generally the result of changes in data supplied by other U.S. government agencies or organizations, as they continue to make refinements and improvements. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate.

Below are categories with recalculations resulting in an average change over the time series of greater than 2.5 MMT CO_2 Eq.

- Natural Gas Systems (CH_4)
- Land Converted to Grassland: Changes in all Ecosystem Carbon Stocks (CO_2)
- Wastewater Treatment (N_2O)
- Manure Management (CH_4)

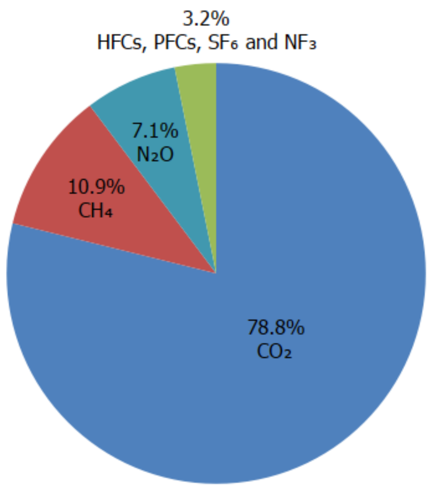
In addition, the Inventory includes new categories not included in the previous Inventory that improve completeness of the national estimates. Specifically, the current report includes CH_4 emissions from post-meter uses (i.e., includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles), fugitive CO_2 emissions from coal mining, CO_2 emissions from land converted to flooded land (i.e., lands converted to use as reservoirs and other constructed water bodies), CH_4 emissions from land remaining and land converted to flooded land, and PFC (CF_4) emissions from electrical transmission and distribution.

In each Inventory, the results of all methodological changes and historical data updates and inclusion of new sources and sink estimates are summarized in the Recalculations and Improvements chapter (Chapter 9). For more detailed descriptions of each recalculation including references for data, please see the respective source or sink category description(s) within the relevant report chapter (i.e., Energy chapter (Chapter 3), the Industrial Process and Product Use (IPPU) chapter (Chapter 4) the Agriculture chapter (Chapter 5), the Land Use, Land Use Change and Forestry (LULUCF) chapter (Chapter 6), and the Waste chapter (Chapter 7)). In implementing improvements, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is good practice to change or refine methods when: available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; new inventory methods become available; and for correction of errors."

Emissions by Gas

Figure ES-3 illustrates the relative contribution of the greenhouse gases to total U.S. emissions in 2020, weighted by global warming potential. The primary greenhouse gas emitted by human activities in the United States was CO_2, representing 78.8 percent of total greenhouse gas emissions. The largest source of CO_2, and of overall greenhouse gas emissions, was fossil fuel combustion primarily from transportation and power generation. Methane (CH_4) emissions account for 10.9 percent of emissions. The major sources of methane include enteric fermentation associated with domestic livestock, natural gas systems, and decomposition of wastes in landfills. Agricultural soil management, wastewater treatment, stationary sources of fuel combustion, and manure management were the major sources of N_2O emissions. Ozone depleting substance substitute emissions was the primary contributor to aggregate hydrofluorocarbon (HFC) emissions. Perfluorocarbon (PFC) emissions were primarily attributable to electronics manufacturing and primary aluminum production. Electrical transmission and distribution systems accounted for most sulfur hexafluoride (SF_6) emissions. The electronics industry is the only source of nitrogen trifluoride (NF_3) emissions.

Figure ES-3: 2020 U.S. Greenhouse Gas Emissions by Gas (Percentages based on MMT CO_2 Eq.)



From 1990 to 2020, total emissions of CO_2 decreased by 406.8 MMT CO_2 Eq. (7.9 percent), total emissions of CH_4 decreased by 130.4 MMT CO_2 Eq. (16.7 percent), and emissions of N_2O decreased by 24.4 MMT CO_2 Eq. (5.4 percent). During the same period, emissions of fluorinated greenhouse gases including HFCs, PFCs, SF_6, and NF_3 rose by 89.5 MMT CO_2 Eq. (89.8 percent). From 1990 to 2020, emissions of HFCs increased by 132.2 MMT CO_2 Eq. (284.3 percent) and NF_3 emissions increased by 0.6 MMT CO_2 Eq. (1,195.3 percent), while emissions of PFCs decreased by 19.8 MMT CO_2 Eq. (81.8 percent) and SF_6 emissions decreased by 23.4 MMT CO_2 Eq. (81.3 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6 and NF_3 are significant because many of these gases have extremely high global warming potentials and, in the cases of PFCs and SF_6, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in forests, trees in urban areas, agricultural soils, landfilled yard trimmings and food scraps, and coastal wetlands, which together offset 13.6 percent of total emissions in 2020 (as reflected in

Figure ES-1). The following sections describe each gas's contribution to total U.S. greenhouse gas emissions in more detail.

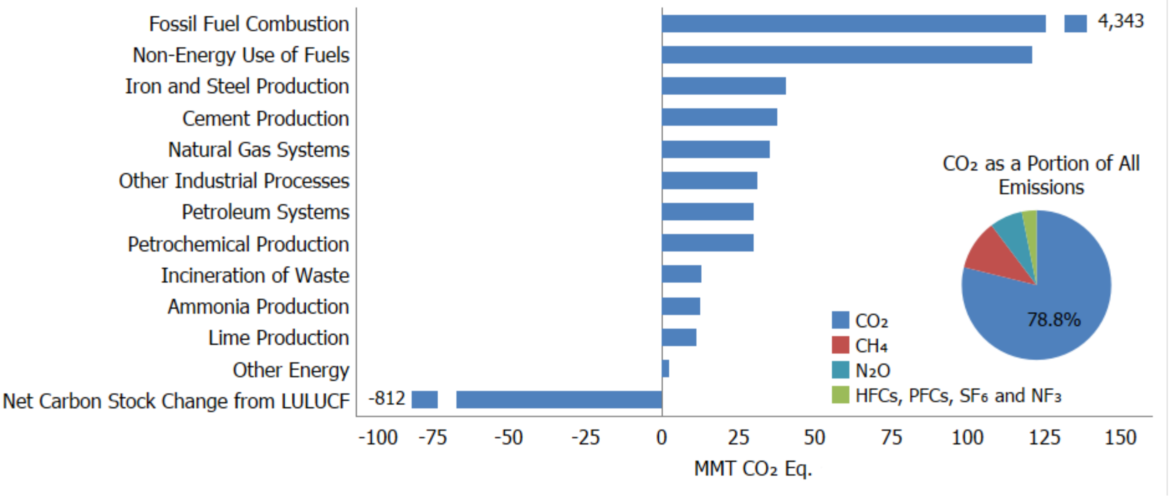
Carbon Dioxide Emissions

The global carbon cycle is made up of large carbon flows and reservoirs. Billions of tons of carbon in the form of CO_2 are absorbed by oceans and living biomass (i.e., sinks) and are emitted to the atmosphere annually through natural processes (i.e., sources). When in equilibrium, global carbon fluxes among these various reservoirs are roughly balanced.[13]

Since the Industrial Revolution (i.e., about 1750), global atmospheric concentrations of CO_2 have risen 47.9 percent (IPCC 2013; NOAA/ESRL 2022a), principally due to the combustion of fossil fuels for energy. Globally, an estimated 31,500 MMT of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2019, of which the United States accounted for 15.4 percent.[14]

Within the United States, fossil fuel combustion accounted for 92.1 percent of CO_2 emissions in 2020. Transportation was the largest emitter of CO_2 in 2020 followed by electric power generation. There are 26 additional sources of CO_2 emissions included in the Inventory (see Table 2-1). Although not illustrated in Table ES-4, changes in land use and forestry practices can also lead to net CO_2 emissions (e.g., through conversion of forest land to agricultural or urban use) or to a net sink for CO_2 (e.g., through net additions to forest biomass). See more on these emissions and removals in Table ES-4.

Figure ES-4: 2020 Sources of CO_2 Emissions



Note: Emissions from Aluminum Production, Carbide Production, Carbon Dioxide Consumption, Ferroalloy Production, Lead Production, Magnesium Production, Other Process Uses of Carbonates, Phosphoric Acid Production, Soda Ash, Titanium Dioxide, Urea Consumption, and Zinc Production are included in Other Industrial Processes. Emissions from Abandoned Oil and Gas Wells and Coal Mining are included in Other Energy.

As the largest source of U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for 75.3 percent of GWP-weighted total U.S. gross emissions across the time series. Between 1990 and 2020, CO_2 emissions from fossil fuel combustion decreased from 4,731.2 MMT CO_2 Eq. to 4,342.7 MMT CO_2 Eq., an 8.2 percent total

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[13] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

[14] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *CO_2 Emissions from Fossil Fuels Combustion Overview.* See https://webstore.iea.org/co2-emissions-from-fuel-combustion-2020-highlights (IEA 2021). The publication has not yet been updated to include complete global 2020 data.

decrease. Conversely, CO_2 emissions from fossil fuel combustion decreased by 1,409.4 MMT CO_2 Eq. from 2005 levels, a decrease of 24.5 percent. From 2019 to 2020, these emissions decreased by 509.7 MMT CO_2 Eq. (10.5 percent).

Historically, changes in emissions from fossil fuel combustion have been the driving factor affecting U.S. emission trends. Changes in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. Important drivers include: (1) changes in demand for energy; and (2) a general decline in the carbon intensity of fuels combusted for energy in recent years by non-transport sectors of the economy. Long-term factors affecting energy demand include population and economic trends, technological changes including energy efficiency, shifting energy fuel choices, and various policies at the national, state, and local level. In the short term, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. Between 2019 and 2020, reduced economic activity and decreased travel due to the COVID-19 pandemic had significant impacts on energy use and fossil fuel combustion emissions.

The five major fuel-consuming economic sectors are transportation, electric power, industrial, residential, and commercial and are described below. Carbon dioxide emissions are produced by the electric power sector as fossil fuel is consumed to provide electricity to one of the other four sectors, or "end-use" sectors, see Figure ES-5. Note that this Figure reports emissions from U.S. Territories as their own end-use sector due to incomplete data for their individual end-use sectors. Fossil fuel combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure ES-5: 2020 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type

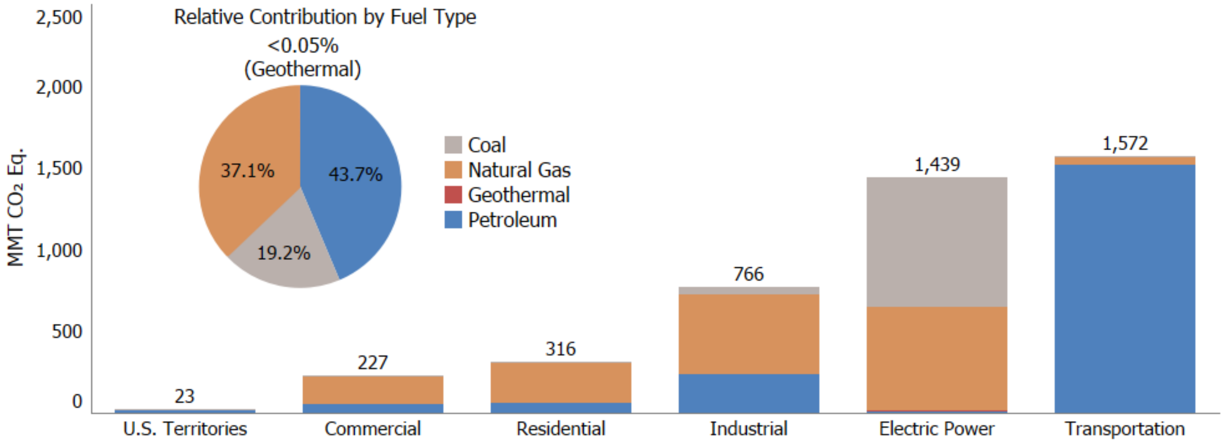
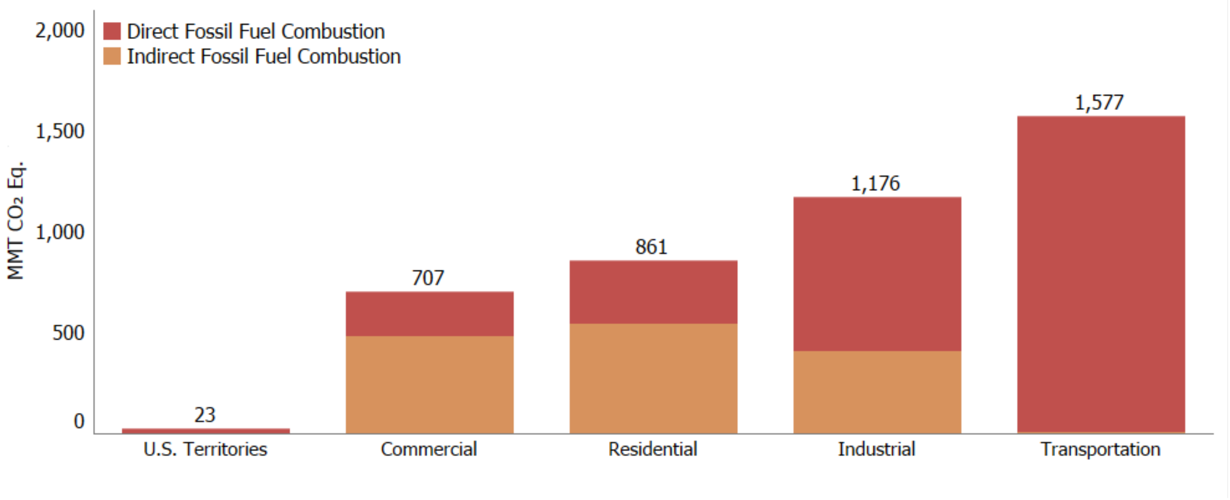


Table ES-6 summarizes CO_2 emissions from fossil fuel combustion by end-use sector including electric power emissions. For Figure ES-6, electric power emissions have been distributed to each end-use sector on the basis of each sector's share of aggregate electricity use (i.e., indirect fossil fuel combustion). This method of distributing emissions assumes that each end-use sector uses electricity that is generated from the national average mix of fuels according to their carbon intensity. Emissions from electric power are also addressed separately after the end-use sectors are discussed.

Figure ES-6: 2020 End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Transportation End-Use Sector. Transportation activities accounted for 36.2 percent of U.S. CO_2 emissions from fossil fuel combustion in 2020, with the largest contributors being passenger vehicles (38.5 percent), followed by freight trucks (26.3 percent) and light-duty trucks (18.9 percent). Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

In terms of the overall trend, from 1990 to 2020, total transportation CO_2 emissions increased due, in large part, to increased demand for travel[15] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period. From 2019 to 2020, transportation CO_2 emissions decreased 13.3 percent, primarily as a result of the COVID-19 pandemic and associated restrictions that led to less travel. While an increased demand for travel has led to generally increasing CO_2 emissions since 1990, improvements in average new vehicle fuel economy since 2005 has slowed the rate of increase of CO_2 emissions. In 2020, petroleum-based products supplied 94.5 percent of the energy consumed for transportation, primarily from gasoline consumption in automobiles and other highway vehicles (57.3 percent), diesel fuel for freight trucks (26.5 percent), jet fuel for aircraft (9.6 percent), and natural gas, residual fuel, aviation gasoline, and liquefied petroleum gases (1.0 percent). The remaining 5.5 percent is associated with renewable fuels (i.e., biofuels).

Industrial End-Use Sector. Industrial CO_2 emissions, resulting both directly from the combustion of fossil fuels and indirectly from the generation of electricity that is used by industry, accounted for 27.1 percent of CO_2 emissions from fossil fuel combustion in 2020. Approximately 65.2 percent of these emissions resulted from direct fossil fuel combustion to produce steam and/or heat for industrial processes. The remaining emissions resulted from the use of electricity for motors, electric furnaces, ovens, lighting, and other applications. Total direct and indirect emissions from the industrial sector have declined by 22.0 percent since 1990. This decline is due to structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements. From 2019 to 2020, total energy use in the industrial sector decreased by 4.4 percent partially as a result of reductions in economic and manufacturing activity due to the COVID-19 pandemic.

Residential and Commercial End-Use Sectors. The residential and commercial end-use sectors accounted for 19.8 and 16.3 percent, respectively, of CO_2 emissions from fossil fuel combustion in 2020. The residential and commercial sectors relied heavily on electricity for meeting energy demands, with 63.3 and 67.9 percent, respectively, of their emissions attributable to electricity use for lighting, heating, cooling, and operating

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[15] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2020 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

appliances. The remaining emissions were due to the consumption of natural gas and petroleum for heating and cooking. Total direct and indirect emissions from the residential sector have decreased by 7.6 percent since 1990. Total direct and indirect emissions from the commercial sector have decreased by 7.7 percent since 1990. From 2019 to 2020, a decrease in heating degree days (9.4 percent) reduced energy demand for heating in the residential and commercial sectors. This was partially offset by a 1.5 percent increase in cooling degree days compared to 2019, which impacted demand for air conditioning in the residential and commercial sectors. This, combined with people staying home in response to the COVID-19 pandemic, resulted in a 1.7 percent increase in residential sector electricity use. From 2019 to 2020, the COVID-19 pandemic reduced economic and manufacturing activity which contributed to 5.4 percent lower energy use in the commercial sector.

Electric Power. The United States relies on electricity to meet a significant portion of its energy demands. Electricity generators used 31.2 percent of U.S. energy from fossil fuels and emitted 33.1 percent of the CO_2 from fossil fuel combustion in 2020. The type of energy source used to generate electricity is the main factor influencing emissions.[16] The mix of fossil fuels used also impacts emissions. The electric power sector is the largest consumer of coal in the United States. The coal used by electricity generators accounted for 91.4 percent of all coal consumed for energy in the United States in 2020.[17] However, the amount of coal and the percent of total electricity generation from coal has been decreasing over time. Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54.2 percent of generation in 1990 to 19.9 percent in 2020.[18] This corresponded with an increase in natural gas generation and non-fossil fuel renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 10.7 percent of electric power generation in 1990 and increased over the thirty-one-year period to represent 39.5 percent of electric power generation in 2020. Wind and solar generation (in kWh) represented 0.1 percent of electric power generation in 1990 and increased over the thirty-one-year period to represent 11.1 percent of electric power generation in 2020. Economic impacts of the COVID-19 pandemic, combined with a warmer winter, led to a decrease in electricity use of about 2.5 percent in 2020, and the trend of decreased coal use and increased use of natural gas and renewable energy continued. Between 2019 and 2020, coal electricity generation dropped by 19.9 percent, natural gas generation increased by 2.9 percent, and renewable energy generation increased by 7.9 percent.

Across the time series, changes in electricity generation and the carbon intensity of fuels used for electric power have a significant impact on CO_2 emissions. While CO_2 emissions from fossil fuel combustion from the electric power sector have decreased by 20.9 percent since 1990, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has significantly decreased during that same timeframe by 19.2 percent. This decoupling of the level of electric power generation and the resulting CO_2 emissions is shown in Figure ES-7.

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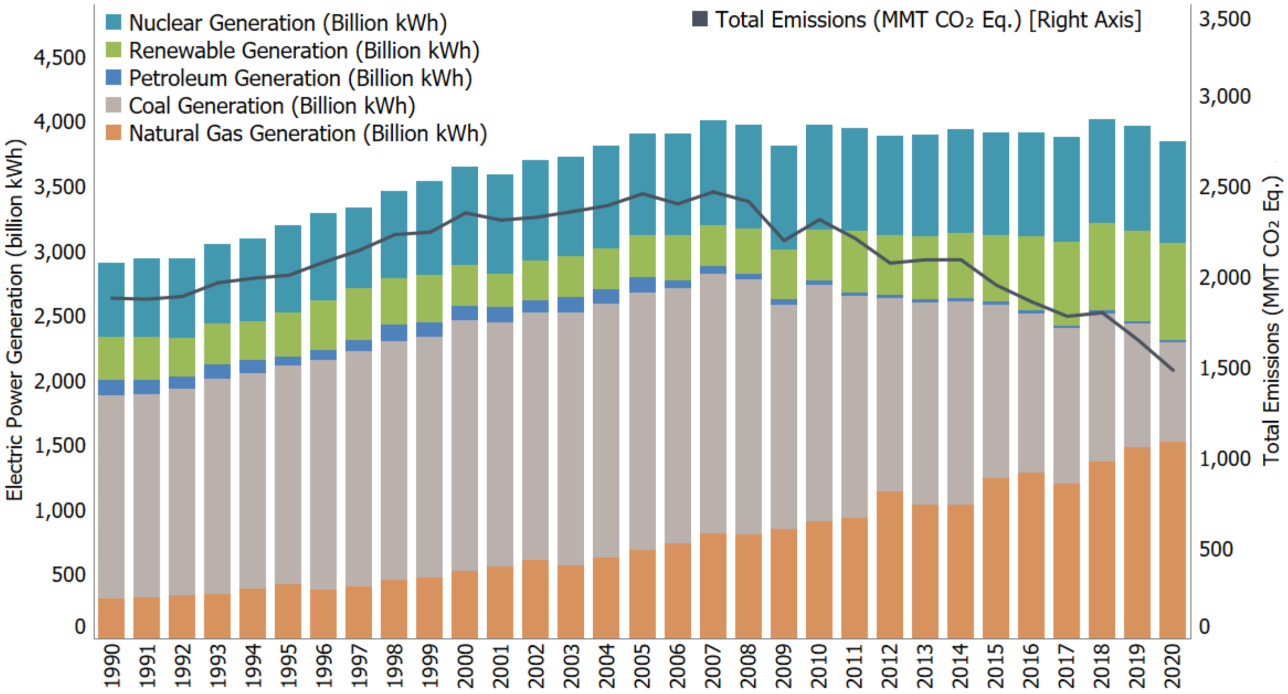
[16] In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not included in the electricity sector totals and trends discussed in this section. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[17] See Table 6.2 Coal Consumption by Sector of EIA (2022a).

[18] Values represent electricity *net* generation from the electric power sector. See Table 7.2b Electricity Net Generation: Electric Power Sector of EIA (2022a).

Figure ES-7: Electric Power Generation and Emissions



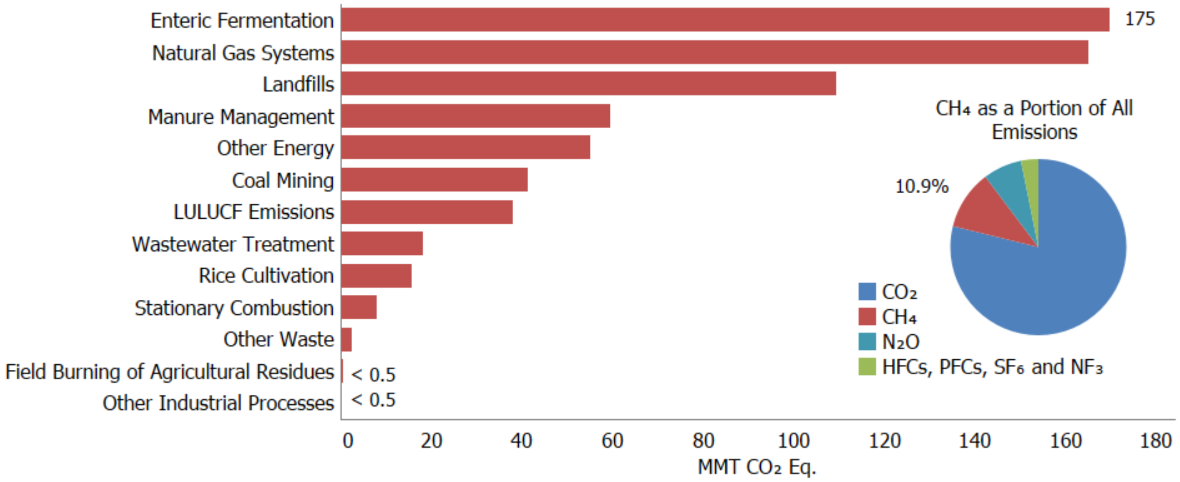
Other significant CO_2 trends included the following:

- Carbon dioxide emissions from natural gas and petroleum systems increased by 24.0 MMT CO_2 Eq. (57.9 percent) from 1990 to 2020. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.
- Carbon dioxide emissions from iron and steel production and metallurgical coke production have decreased by 67.0 MMT CO_2 Eq. (64.0 percent) from 1990 through 2020. This decrease is primarily due to restructuring of the industry, technological improvements, and increased scrap steel utilization.
- Total C stock change (i.e., net CO_2 removals) in the LULUCF sector decreased by 9.0 percent between 1990 and 2020. This decrease was primarily due to a decrease in the rate of net C accumulation in forest C stocks and *Cropland Remaining Cropland,* as well as an increase in emissions from *Land Converted to Settlements*.

Methane Emissions

Methane (CH_4) is significantly more effective than CO_2 at trapping heat in the atmosphere–by a factor of 25 over a 100-year time frame based on the *IPCC Fourth Assessment Report* estimate (IPCC 2007). Over the last two hundred and fifty years, the concentration of CH_4 in the atmosphere increased by 168.4 percent (IPCC 2013; NOAA/ESRL 2022b). Within the United States, the main anthropogenic sources of CH_4 include enteric fermentation from domestic livestock, natural gas systems, landfills, domestic livestock manure management, coal mining, and petroleum systems (see Figure ES-8).

Figure ES-8: 2020 Sources of CH_4 Emissions



Note: Methane emissions from Abandoned Oil and Gas Wells, Abandoned Underground Coal Mines, Incineration of Waste, and Mobile Combustion are included in Other Energy. Methane emissions from anaerobic digestion at biogas facilities and composting are included in Other Waste. Methane emissions from Carbide Production and Consumption, Ferroalloy Production, Iron and Steel Production, and Petrochemical Production are included in Other Industrial Processes. LULUCF emissions include the CH_4 reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*, *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land.

Significant trends for the largest sources of U.S. CH_4 emissions include the following:

- Enteric fermentation was the largest anthropogenic source of CH_4 emissions in the United States in 2020, accounting for 175.2 MMT CO_2 Eq. of CH_4 (26.9 percent of total CH_4 emissions) and representing an increase of 11.7 MMT CO_2 Eq. (7.2 percent) since 1990. This increase in emissions from 1990 to 2020 generally follows the increasing trends in cattle populations.

- Natural gas systems were the second largest anthropogenic source category of CH_4 emissions in the United States in 2020, accounting for 164.9 MMT CO_2 Eq. of CH_4 (25.4 percent of total CH_4 emissions). Emissions decreased by 30.6 MMT CO_2 Eq. (15.7 percent) since 1990 largely due to decreases in emissions from distribution, transmission, and storage.

- Landfills were the third largest anthropogenic source of CH_4 emissions in the United States in 2020, accounting for 109.3 MMT CO_2 Eq. (16.8 percent of total CH_4 emissions) and representing a decrease of 67.2 MMT CO_2 Eq. (38.1 percent) since 1990, with small year-to-year increases. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in MSW landfills over the time series.[19]

Nitrous Oxide Emissions

Nitrous oxide (N_2O) is produced by biological processes that occur in soil and water and by a variety of anthropogenic activities in the agricultural, energy, industrial, and waste management fields. While total N_2O emissions are much lower than CO_2 emissions, N_2O is nearly 300 times more powerful than CO_2 at trapping heat in the atmosphere over a 100-year time frame (IPCC 2007). Since 1750, the global atmospheric concentration of N_2O has risen by 23.3 percent (IPCC 2013; NOAA/ESRL 2022c). The main anthropogenic activities producing N_2O in the

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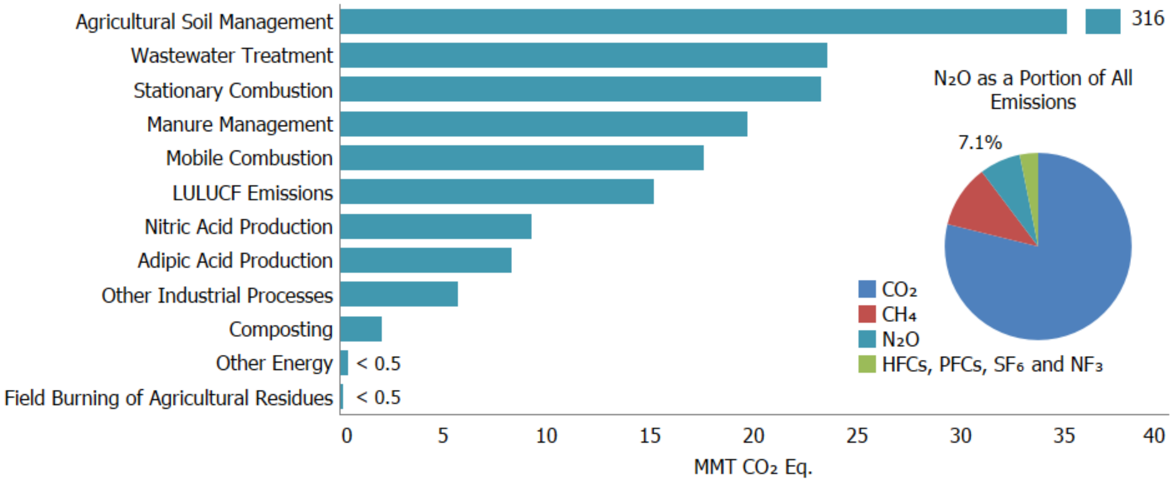
[19] Carbon dioxide emissions from landfills are not included specifically in summing waste sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs and decay of disposed wood products are accounted for in the estimates for LULUCF.

United States are agricultural soil management, wastewater treatment, stationary fuel combustion, manure management, fuel combustion in motor vehicles, and nitric acid production (see Figure ES-9).

Figure ES-9: 2020 Sources of N_2O Emissions



Note: Nitrous oxide emissions from Petroleum Systems, Natural Gas Systems, and Incineration of Waste are included in Other Energy. Nitrous oxide emissions from Caprolactam, Glyoxal, and Glyoxylic Acid Production, Electronics Industry, and Product Uses are included in Other Industrial Processes. LULUCF emissions include N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, *Coastal Wetlands Remaining Coastal Wetlands*, Forest Soils and Settlement Soils.

Significant trends for the largest sources of U.S. emissions of N_2O include the following:

- Agricultural soils were the largest anthropogenic source of N_2O emissions in 2020, accounting for 316.2 MMT CO_2 Eq. (74.2 percent of N_2O emissions) and 5.3 percent of total greenhouse gas emissions in the United States. These emissions increased by 0.2 MMT CO_2 Eq. (0.1 percent) from 1990 to 2020, but have fluctuated during that period due to annual variations in weather patterns, fertilizer use, and crop production.

- Wastewater treatment, both domestic and industrial, was the second largest anthropogenic source of N_2O emissions in 2020, accounting for 23.5 MMT CO_2 Eq. (5.5 percent of N_2O emissions) and 0.4 percent of total greenhouse gas emissions in the United States in 2020. Emissions from wastewater treatment increased by 6.9 MMT CO_2 Eq. (41.8 percent) since 1990 as a result of growing U.S. population and protein consumption. Nitrous oxide emissions from industrial wastewater treatment sources fluctuated throughout the time series with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries.

- Nitrous oxide emissions from manure management accounted for 19.7 MMT CO_2 Eq. (4.6 percent of N_2O emissions) and 0.3 percent of total greenhouse gas emissions in the United States in 2020. These emissions increased by 5.7 MMT CO_2 Eq. (41.2 percent) from 1990 to 2020. While the industry trend has been a shift toward liquid systems, driving down the emissions per unit of nitrogen excreted (dry manure handling systems have greater aerobic conditions that promote N_2O emissions), increases in specific animal populations have driven an increase in overall manure management N_2O emissions over the time series.

- Nitrous oxide emissions from mobile combustion decreased by 27.2 MMT CO_2 Eq. (61.0 percent) from 1990 to 2020, primarily as a result of national vehicle emissions standards and emission control technologies for on-road vehicles.

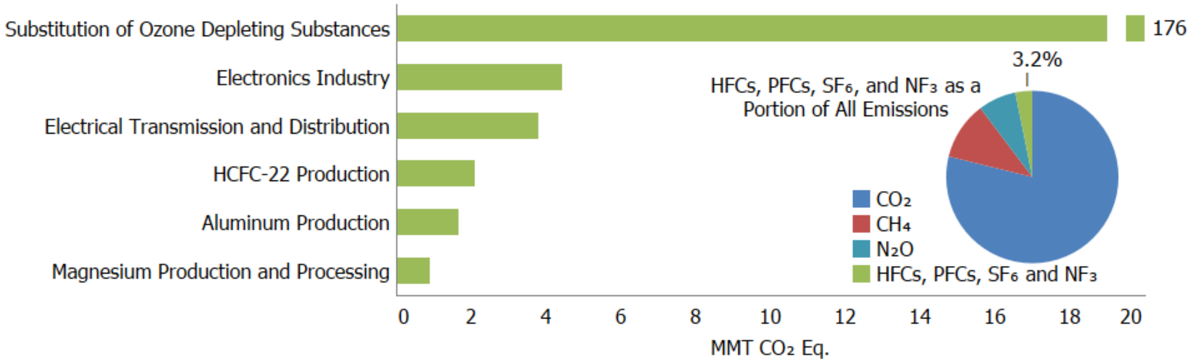
HFC, PFC, SF_6, and NF_3 Emissions

Hydrofluorocarbons (HFCs) are synthetic chemicals that are used as alternatives to ozone depleting substances (ODS), which are being phased out under the Montreal Protocol and Clean Air Act Amendments of 1990. Hydrofluorocarbons do not deplete the stratospheric ozone layer and therefore have been used as alternatives under the Montreal Protocol on Substances that Deplete the Ozone Layer.

Perfluorocarbons (PFCs) are emitted from the production of electronics and aluminum and also (in smaller quantities) from their use as alternatives to ozone depleting substances. Sulfur hexafluoride (SF_6) is emitted from the manufacturing and use of electrical transmission and distribution equipment as well as the production of electronics and magnesium. NF_3 is emitted from electronics production. One HFC, HFC-23, is emitted during production of HCFC-22 and electronics (see Figure ES-10).

HFCs, PFCs, SF_6, and NF_3 are potent greenhouse gases. In addition to having very high global warming potentials, SF_6, NF_3, and PFCs have extremely long atmospheric lifetimes, resulting in their essentially irreversible accumulation in the atmosphere once emitted. Sulfur hexafluoride is the most potent greenhouse gas the IPCC has evaluated (IPCC 2021).

Figure ES-10: 2020 Sources of HFCs, PFCs, SF_6, and NF_3 Emissions



Some significant trends for the largest sources of U.S. HFC, PFC, SF_6, and NF_3 emissions include the following:

- Hydrofluorocarbon and perfluorocarbon emissions resulting from their use as substitutes for ODS (e.g., chlorofluorocarbons [CFCs]) are the largest share of fluorinated emissions (93.2 percent) in 2020 and have been consistently increasing, from small amounts in 1990 to 176.3 MMT CO_2 Eq. in 2020. This increase was in large part the result of efforts to phase out CFCs and other ODS in the United States.
- PFC, HFC, SF_6, and NF_3 emissions from the electronics industry have increased by 24.7 percent from 1990 to 2020, reflecting the competing influences of industrial growth and the adoption of emission reduction technologies. Within that time span, emissions peaked at 9.0 MMT CO_2 Eq. in 1999, the initial year of EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry, and have since declined to 4.4 MMT CO_2 Eq. in 2020 (a 50.9 percent decrease relative to 1999).
- Sulfur hexafluoride emissions from electric power transmission and distribution systems decreased by 83.6 percent (19.4 MMT CO_2 Eq.) from 1990 to 2020. There are two factors contributing to this decrease: (1) a sharp increase in the price of SF_6 during the 1990s and (2) a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's SF_6 Emission Reduction Partnership for Electric Power Systems.
- Emissions from HCFC-22 production were 2.1 MMT CO_2 Eq. in 2020, a 95.4 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by a reduction in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The emission rate was lowered by optimizing the production process and capturing much of the remaining HFC-23 for use or destruction.

- PFC emissions from aluminum production decreased by 92.2 percent (19.8 MMT CO_2 Eq.) from 1990 to 2020, due to both industry emission reduction efforts and lower domestic aluminum production.

ES.3 Overview of Sector Emissions and Trends

Figure ES-11 and Table ES-3 aggregate emissions and sinks by the sectors defined by the UNFCCC reporting guidelines to promote comparability across countries. Over the thirty-one-year period of 1990 to 2020, total emissions from the Industrial Processes and Product Use, and Agriculture sectors grew by, 30.2 MMT CO_2 Eq. (8.7 percent), and 42.8 MMT CO_2 Eq. (7.8 percent), respectively. Emissions from the Energy and Waste sectors decreased by 486.5 MMT CO_2 Eq. (9.1 percent) and 58.6 MMT CO_2 Eq. (27.4 percent) respectively. Over the same period, net carbon (C) sequestration in the LULUCF sector decreased by 79.8 MMT CO_2 (9.0 percent decrease in total net C sequestration), while emissions from the LULUCF sector (i.e., CH_4 and N_2O) increased by 21.8 MMT CO_2 Eq. (69.6 percent).

Figure ES-11: U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector/Category

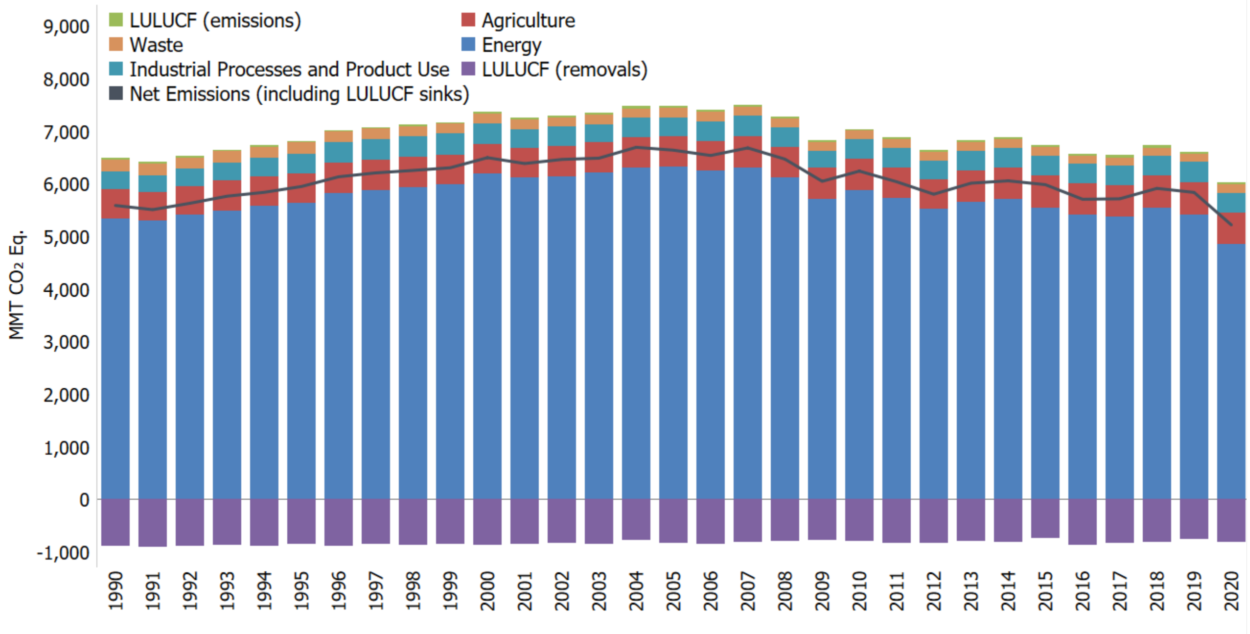


Table ES-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector/Category (MMT CO_2 Eq.)

IPCC Sector/Category	1990	2005	2016	2017	2018	2019	2020
Energy	5,341.1	6,319.8	5,413.1	5,372.7	5,539.5	5,409.8	4,854.7
Industrial Processes and Product Use	346.2	365.9	369.0	369.4	373.4	379.5	376.4
Agriculture	551.9	573.6	601.9	603.2	616.7	622.9	594.7
Waste	214.2	175.6	153.9	155.7	157.9	159.6	155.6
Total Gross Emissions[a] (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[b]	(860.6)	(789.8)	(826.6)	(781.2)	(769.3)	(730.5)	(758.9)
Net Emissions (Sources and Sinks)[c]	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

[a] Total emissions without LULUCF.

[b] The LULUCF Sector Net Total is the sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

[c] Net emissions with LULUCF.

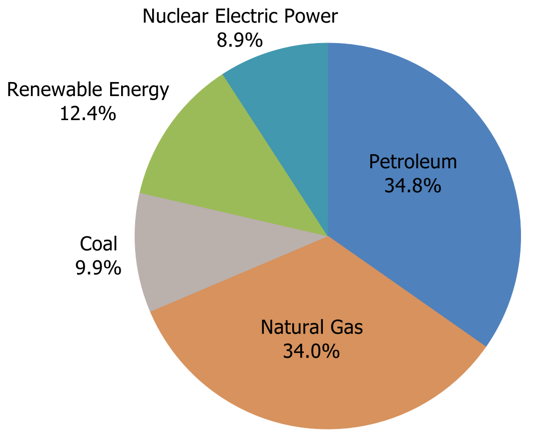
Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

The Energy chapter contains emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and the use of fossil fuels for non-energy purposes. Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2020. Energy-related activities are also responsible for CH_4 and N_2O emissions (41.4 percent and 9.6 percent of total U.S. emissions of each gas, respectively). Overall, emission sources in the Energy chapter account for a combined 81.2 percent of total U.S. greenhouse gas emissions in 2020.

In 2020, 78.8 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 21.2 percent came from other energy sources, such as hydropower, biomass, nuclear, wind, and solar energy (see Figure ES-12).

Figure ES-12: 2020 U.S. Energy Consumption by Energy Source (Percent)



Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter contains information on greenhouse gas emissions generated and emitted as the byproducts of non-energy-related industrial processes, which involve the chemical or physical transformation of raw materials and can release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). These processes include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption. Most of these industries also emit CO_2 from fossil fuel combustion which, in line with IPCC sectoral definitions, is included in the Energy Sector.

This chapter also contains information on the release of HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds used in industrial manufacturing processes and by end-consumers (e.g., residential and mobile air conditioning). These industries include electronics industry, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by electronics industry and anesthetic and aerosol applications, and CO_2 is consumed and emitted through various end-use applications. In 2020, emissions resulting from use of the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) by end-consumers was the largest source of IPPU emissions and accounted for 176.3 MMT CO_2 Eq, or 46.8 percent of total IPPU emissions.

IPPU activities are responsible for 3.5, 0.1, and 5.5 percent of total U.S. CO_2, CH_4, and N_2O emissions respectively as well as for all U.S. emissions of fluorinated gases including HFCs, PFCs, SF_6 and NF_3. Overall, emission sources in the IPPU chapter accounted for 6.3 percent of U.S. greenhouse gas emissions in 2020.

Agriculture

The Agriculture chapter contains information on anthropogenic emissions from agricultural activities (except fuel combustion, which is addressed in the Energy chapter, and some agricultural CO_2, CH_4, and N_2O fluxes, which are addressed in the Land Use, Land-Use Change, and Forestry chapter).

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: agricultural soil management, enteric fermentation in domestic livestock, livestock manure management, rice cultivation, urea fertilization, liming, and field burning of agricultural residues.

In 2020, agricultural activities were responsible for emissions of 549.7 MMT CO_2 Eq., or 9.9 percent of total U.S. greenhouse gas emissions. Methane, N_2O, and CO_2 are greenhouse gases emitted by agricultural activities. Methane emissions from enteric fermentation and manure management represented 26.9 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2020. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2020, accounting for 74.2 percent of total N_2O emissions. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities.

Land Use, Land-Use Change, and Forestry

The LULUCF chapter contains emissions and removals of CO_2 and emissions of CH_4 and N_2O from managed lands in the United States. Consistent with the *2006 IPCC Guidelines*, emissions and removals from managed lands are considered to be anthropogenic, while emissions and removals from unmanaged lands are considered to be natural.[20] The share of managed land in the U.S. is approximately 95 percent of total land included in the Inventory.[21] More information on the definition of managed land used in the Inventory is provided in Chapter 6.

Overall, the Inventory results show that managed land is a net sink for CO_2 (C sequestration). The primary drivers of fluxes on managed lands include forest management practices, tree planting in urban areas, the management of agricultural soils, lands remaining and lands converted to reservoirs and other constructed waterbodies, landfilling of yard trimmings and food scraps, and activities that cause changes in C stocks in coastal wetlands. The main drivers for forest C sequestration include forest growth and increasing forest area (i.e., afforestation), as well as a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements,* which occurs predominantly from urban forests (i.e., Settlement Trees) and landfilled yard trimmings and food scraps, is a result of net tree growth and increased urban forest area, as well as long-term accumulation of yard trimmings and food scraps carbon in landfills.

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[20] See http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_01_Ch1_Introduction.pdf.

[21] The current land representation does not include land in U.S. Territories, but there are planned improvements to include these regions in future Inventories. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2 in Chapter 6 of this report.

The LULUCF sector in 2020 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.2 MMT CO_2 Eq.[22] The removals of C offset 13.6 percent of total (i.e., gross) greenhouse gas emissions in 2020. Emissions of CH_4 and N_2O from LULUCF activities in 2020 were 53.2 MMT CO_2 Eq. and represent 0.9 percent of total greenhouse gas emissions.[23] Carbon dioxide removals from C stock changes are presented in Table ES-4 along with CH_4 and N_2O emissions for LULUCF source categories.

Between 1990 and 2020, total C sequestration in the LULUCF sector decreased by 9.0 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland,* as well as an increase in CO_2 emissions from *Land Converted to Settlements*. The overall net flux from LULUCF (i.e., net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 eq.) resulted in a removal of 758.9 MMT CO_2 Eq. in 2020.

Flooded lands were the largest source of CH_4 emissions from the LULUCF sector in 2020, totaling 19.9 MMT CO_2 Eq. (797 kt of CH_4). Forest fires were the second largest source and resulted in CH_4 emissions of 13.6 MMT CO_2 Eq. (545 kt of CH_4), followed by *Coastal Wetlands Remaining Coastal Wetlands* with CH_4 emissions of 3.8 MMT CO_2 Eq. (154 kt of CH_4).

Forest fires were the largest source of N_2O emissions from the LULUCF sector in 2020, totaling 11.7 MMT CO_2 Eq. (39 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2020 totaled 2.5 MMT CO_2 Eq. (8 kt of N_2O).

Table ES-4: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Forest Land Remaining Forest Land[a]	(769.7)	(674.0)	(717.3)	(670.1)	(664.6)	(631.8)	(642.2)
Land Converted to Forest Land[b]	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland[c]	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland[d]	7.1	9.4	8.6	9.9	10.3	13.1	5.1
Land Converted to Grassland[c]	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)
Wetlands Remaining Wetlands[e]	14.7	17.2	15.8	15.9	15.9	15.9	15.8
Land Converted to Wetlands[e]	7.1	1.2	0.6	0.6	0.6	0.6	0.6
Settlements Remaining Settlements[f]	(107.6)	(113.5)	(121.5)	(125.3)	(124.9)	(124.5)	(123.7)
Land Converted to Settlements[c]	60.8	82.8	77.8	77.9	78.0	77.9	77.9
LULUCF Carbon Stock Change/CO_2[g]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF CH_4 and N_2O Emissions[h]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Sector Net Total[i]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products, emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land,* emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, and CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[b] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[c] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

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[22] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[23] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands;* and N_2O emissions from Forest Soils and Settlement Soils.

[d] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland.*

[e] Estimates include CH_4 emissions from Flooded Land Remaining Flooded Land and Land Converted to Flooded Land.

[f] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements because it is not possible to separate the activity data at this time.

[g] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[h] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[i] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Waste

The Waste chapter contains emissions from waste management activities (except incineration of waste, which is addressed in the Energy chapter). Landfills were the largest source of anthropogenic greenhouse gas emissions from waste management activities, generating 109.3 MMT CO_2 Eq. and accounting for 70.3 percent of total greenhouse gas emissions from waste management activities, and 16.8 percent of total U.S. CH_4 emissions.[24] Additionally, wastewater treatment generated emissions of 41.8 MMT CO_2 Eq. and accounted for 26.9 percent of total Waste sector greenhouse gas emissions, 2.8 percent of U.S. CH_4 emissions, and 5.5 percent of U.S. N_2O emissions in 2020. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.3 MMT CO_2 Eq., and 2.0 MMT CO_2 Eq., respectively. Anaerobic digestion at biogas facilities generated CH_4 emissions of 0.2 MMT CO_2 Eq., accounting for 0.1 percent of emissions from the waste sector. Overall, emission sources accounted for in the Waste chapter generated 155.6 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions in 2020.

ES.4 Other Information

Emissions by Economic Sector

Throughout the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC: Energy, IPPU, Agriculture, LULUCF, and Waste. It is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. For more information on trends in the Land use, Land Use Change and Forestry sector, see Section ES.2 Recent Trends in U.S. Greenhouse Gas Emissions and Sinks.

Figure ES-13 shows the trend in emissions by economic sector from 1990 to 2020, and Table ES-5 summarizes emissions from each of these economic sectors.

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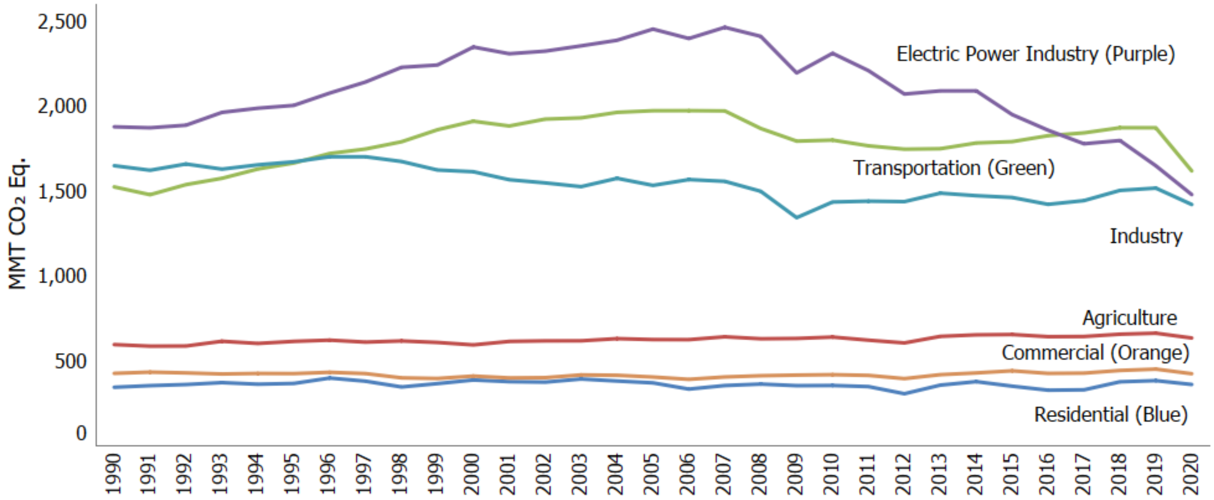
[24] Landfills also store carbon, due to incomplete degradation of organic materials such as harvest wood products, yard trimmings, and food scraps, as described in the Land Use, Land-Use Change, and Forestry chapter of the Inventory report.

Figure ES-13: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table ES-5: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2016	2017	2018	2019	2020
Transportation	1,526.4	1,975.5	1,828.0	1,845.2	1,874.7	1,874.3	1,627.6
Electric Power Industry	1,880.5	2,456.7	1,860.5	1,780.6	1,799.8	1,651.0	1,482.2
Industry	1,652.4	1,536.2	1,424.4	1,446.7	1,507.6	1,521.7	1,426.2
Agriculture	596.8	626.3	643.4	644.4	657.9	663.9	635.1
Commercial	427.1	405.4	426.9	428.5	444.2	452.1	425.3
Residential	345.1	371.0	327.8	329.9	377.4	384.2	362.0
U.S. Territories	25.1	63.7	26.8	25.8	25.8	24.6	23.0
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[a]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

[a] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Using this categorization, emissions from transportation activities accounted for the largest portion (27.2 percent) of total U.S. greenhouse gas emissions in 2020. Electric power accounted for the second largest portion (24.8 percent) of U.S. greenhouse gas emissions in 2020, while emissions from industry accounted for the third largest portion (23.8 percent). Emissions from industry have in general declined over the past decade, due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and energy efficiency improvements.

The remaining 24.2 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for 10.6 percent of U.S. emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for 7.1 percent and 6.1 percent of emissions, respectively, and U.S. Territories accounted for 0.4

percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands.

Electricity is ultimately used in the economic sectors described above. Table ES-6 presents greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power generation are allocated to the economic sectors in which the electricity is used). To distribute electricity emissions among end-use sectors, emissions from the source categories assigned to electric power were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to retail sales of electricity for each end-use sector (EIA 2022 and Duffield 2006).[25] These source categories include CO_2 from fossil fuel combustion and the use of limestone and dolomite for flue gas desulfurization, CO_2 and N_2O from incineration of waste, CH_4 and N_2O from stationary sources, and SF_6 from electrical transmission and distribution systems.

When emissions from electricity use are distributed among these end-use sectors, industrial activities and transportation account for the largest shares of U.S. greenhouse gas emissions (30.3 percent and 27.3 percent, respectively) in 2020. The residential and commercial sectors contributed the next largest shares of total U.S. greenhouse gas emissions in 2020 (15.4 and 15.4 percent, respectively). Emissions from the commercial and residential sectors increase substantially when emissions from electricity use are included, due to their relatively large share of electricity use for energy (e.g., lighting, cooling, appliances). Figure ES-14 shows the trend in these emissions by sector from 1990 to 2020.

Table ES-6: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed by Economic Sector (MMT CO_2 Eq.)

Economic Sectors	1990	2005	2016	2017	2018	2019	2020
Industry	2,326.5	2,251.6	1,917.5	1,926.4	1,983.1	1,964.7	1,813.7
Transportation	1,529.6	1,980.3	1,832.4	1,849.6	1,879.5	1,879.1	1,632.4
Residential	957.6	1,247.2	999.9	964.3	1,036.7	984.1	923.1
Commercial	982.7	1,227.4	1,078.6	1,051.7	1,065.3	1,020.1	919.7
Agriculture	631.9	664.6	682.6	683.2	697.1	699.1	669.5
U.S. Territories	25.1	63.7	26.8	25.8	25.8	24.6	23.0
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[a]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

[a] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

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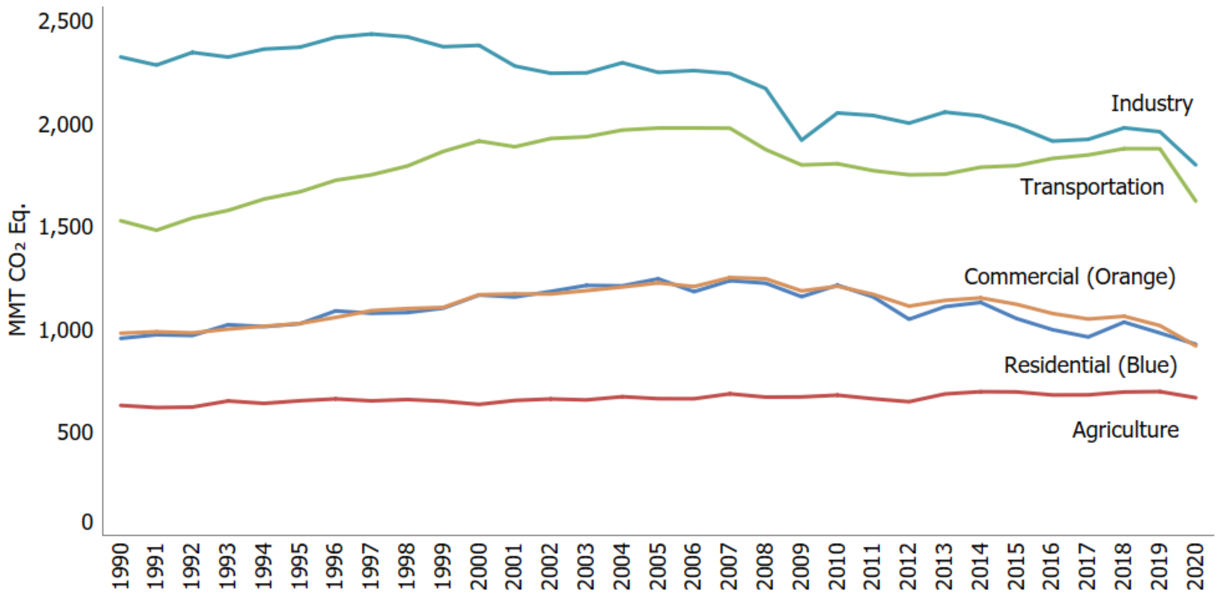
[25] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Figure ES-14: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Box ES-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

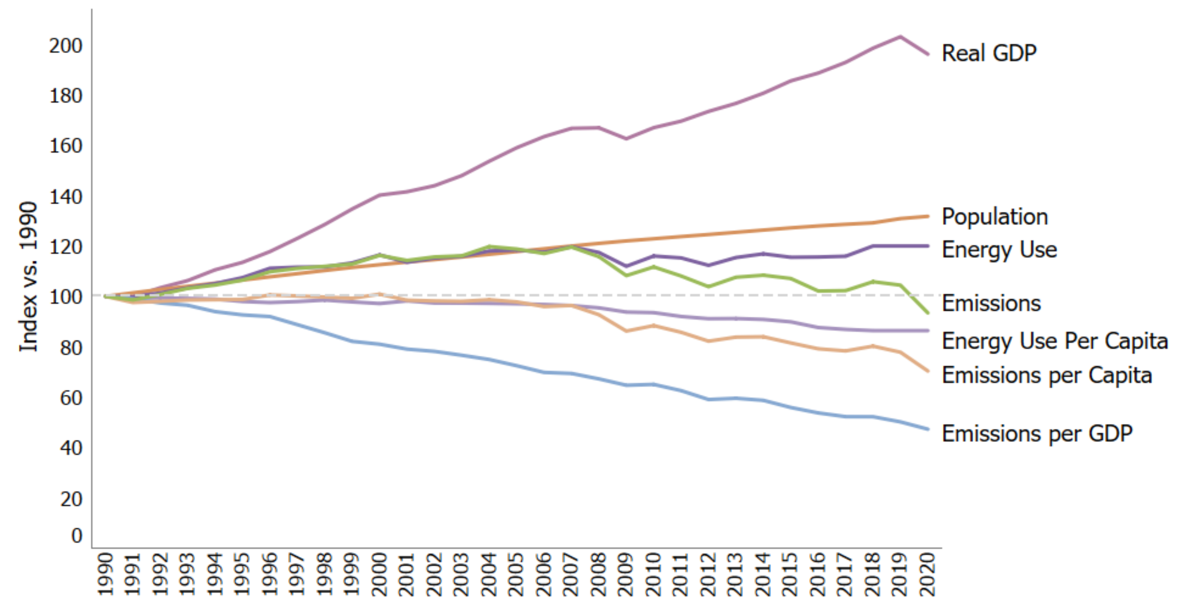
Table ES-7 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have declined at an average annual rate of 0.2 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use and fossil fuel consumption, and overall gross domestic product (GDP), and national population (see Figure ES-15). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use, and fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 1.4 percent since 2005. Fossil fuel consumption has decreased at a slower rate than emissions since 2005, while total energy use, GDP, and national population, generally, continued to increase noting 2020 was impacted by COVID-19 pandemic.

Table ES-7: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2016	2017	2018	2019	2020	Avg. Annual Growth Rate Since 1990[a]	Avg. Annual Growth Rate Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	101	101	104	102	93	-0.2%	-1.4%
Energy Use[c]	100	119	116	116	120	119	109	0.3%	-0.5%
GDP[d]	100	159	189	193	199	203	196	2.3%	1.4%
Population[e]	100	118	128	129	129	131	132	0.9%	0.8%

[a] Average annual growth rate.
[b] GWP-weighted values.
[c] Energy content-weighted values (EIA 2022).
[d] GDP in chained 2009 dollars (BEA 2022).
[e] U.S. Census Bureau (2021).

Figure ES-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product (GDP)



Source: BEA (2021), U.S. Census Bureau (2021), and emission estimates in this report.

Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[26] A key category analysis identifies priority source or sink categories for focusing efforts to improve overall Inventory quality. In addition, a qualitative review of key categories and non-key categories can also help identify additional source and sink categories to consider for improvement efforts, including reducing uncertainty.

Figure ES-16 presents the 2020 key categories identified by the Approach 1 level assessment, including the LULUCF sector. A level assessment using Approach 1 identifies all source and sink categories that cumulatively account for 95 percent of total (i.e., gross) emissions in a given year when assessed in descending order of absolute magnitude.

For a complete list of key categories and more information regarding the overall key category analysis, including approaches accounting for uncertainty and the influence of trends of individual source and sink categories, see the Introduction chapter, Section 1.5 – Key Categories and Annex 1.

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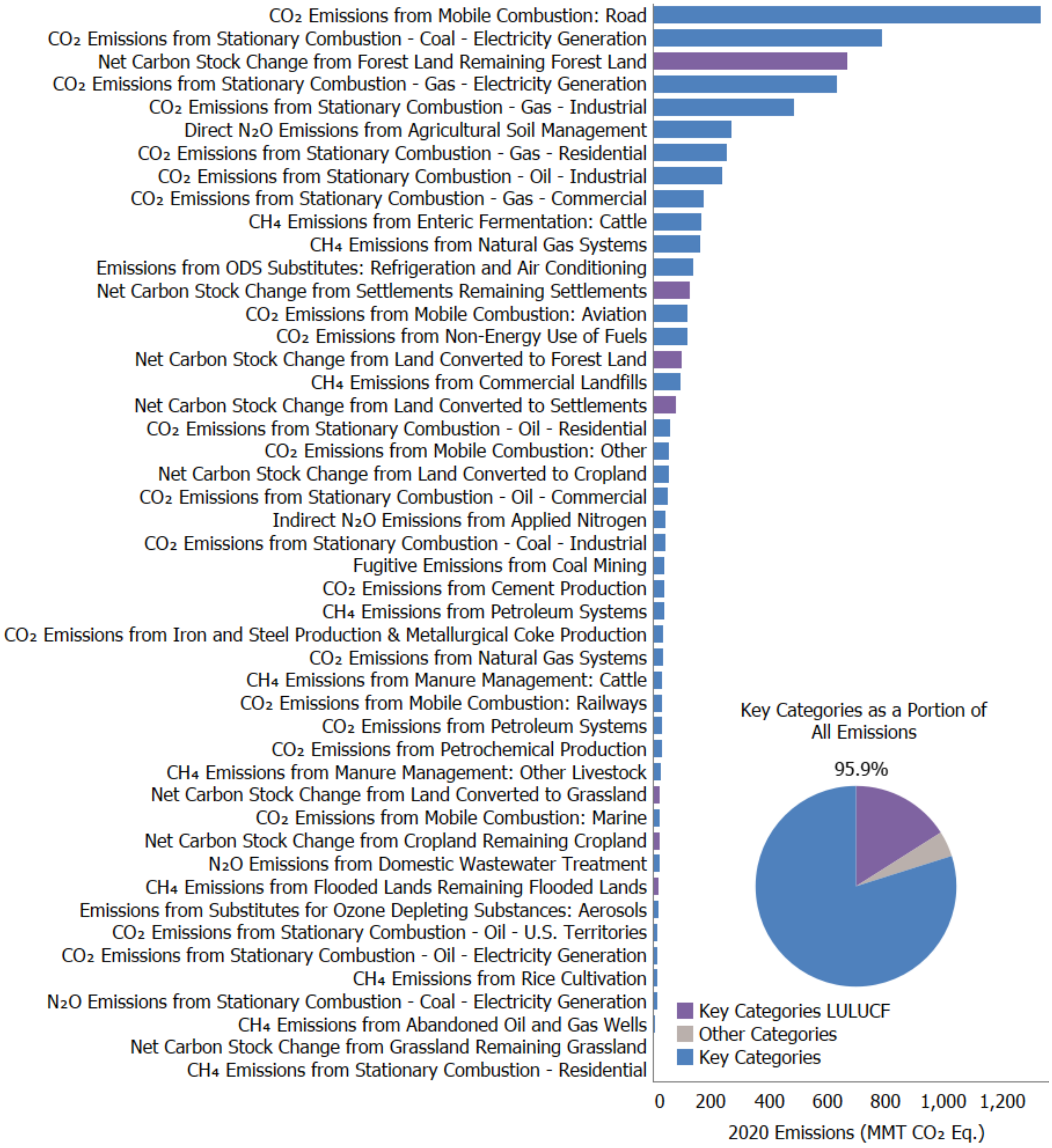
[26] See Chapter 4 "Methodological Choice and Identification of Key Categories" in IPCC (2006). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol1.html.

Figure ES-16: 2020 Key Categories (Approach 1 including LULUCF)[a]



[a] For a complete list of key categories and detailed discussion of the underlying key category analysis, see Annex 1. Bars indicate key categories identified using Approach 1 level assessment including the LULUCF sector. The absolute values of net CO_2 emissions from LULUCF are presented in this figure but reported separately from gross emissions totals. Refer to Table ES-4 for a breakout of emissions and removals for LULUCF by source/sink category.

Quality Assurance and Quality Control (QA/QC)

The United States seeks continuous improvements to the quality, transparency, and usability of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. To assist in these efforts, the United States implemented a systematic approach to QA/QC. The procedures followed for the Inventory have been formalized in accordance with the U.S. Inventory QA/QC plan for the Inventory, and the UNFCCC reporting guidelines and *2006 IPCC Guidelines*. The QA process includes expert and public reviews for both the Inventory estimates and the Inventory report.

Box ES-3: Use of Ambient Measurements Systems for Validation of Emission Inventories

In following the UNFCCC requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and sinks presented in this report are organized by source and sink categories and calculated using internationally accepted methods provided by the IPCC.[27] Several recent studies have estimated emissions at the national or regional level with estimated results that sometimes differ from EPA's estimate of emissions. EPA has engaged with researchers on how remote sensing, ambient measurement, and inverse modeling techniques for estimating greenhouse gas emissions could assist in improving the understanding of inventory estimates. In working with the research community to improve national greenhouse gas inventories, EPA follows guidance from the IPCC on the use of measurements and modeling to validate emission inventories.[28] An area of particular interest in EPA's outreach efforts is how ambient measurement data can be used to assess estimates or potentially be incorporated into the Inventory in a manner consistent with this Inventory report's transparency of its calculation methodologies, and the ability of these techniques to attribute emissions and removals from remote sensing to anthropogenic sources, as defined by the IPCC for this report, versus natural sources and sinks.

The *2019 Refinement to the IPCC 2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1 General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC [2019] Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC [2019] Volume 1, Chapter 6) given the technical complexity of such comparisons. Further, it identified fluorinated gases as one of most suitable greenhouse gases for such comparisons. The *2019 Refinement* makes this conclusion on fluorinated gases based on the lack of confounding natural sources, the potential uncertainties in bottom-up inventory methods, the long atmospheric lifetimes of many of these gases, and the well-known loss mechanisms. Unlike most other gases in the Inventory, since there are no known natural sources of hydrofluorocarbons (HFCs), the HFC emission sources included in this Inventory account for the majority of total emissions detectable in the atmosphere, and the estimates derived from atmospheric measurements are driven solely by anthropogenic emissions. More information on findings from applying this guidance in comparing recent HFC emission studies conducted by NOAA with modeled bottom-up emissions are included under the QA/QC and Verification discussion in Chapter 4, Section 4.24 Substitution of Ozone Depleting Substances in the IPPU chapter of this report.

Consistent with the *2019 Refinement*, a key element to facilitate such comparisons is a gridded prior inventory as an input to inverse modeling. To improve the ability to compare the national-level greenhouse gas inventory with measurement results that may be at other scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1° x 0.1° spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization. The gridded inventory is designed to be consistent with the 1990 to 2014 U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks* estimates for the year 2012, which presents national totals for different source types.[29] This gridded inventory is consistent with the recommendations contained in two National Academies of Science reports examining greenhouse gas emissions data (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2018).

Finally, in addition to use of atmospheric concentration measurement data for comparison with Inventory data, in this year's Inventory, information from top-down studies has been directly incorporated in the Natural Gas Systems calculations to quantify emissions from well blowout events. For more information, see Recalculations

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[27] See http://www.ipcc-nggip.iges.or.jp/public/index.html.

[28] See http://www.ipcc-nggip.iges.or.jp/meeting/pdffiles/1003_Uncertainty%20meeting_report.pdf.

[29] See https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions.

Discussion section in 3.6 Natural Gas Systems.

Uncertainty Analysis of Emission Estimates

Uncertainty assessment is an essential element of a complete inventory of greenhouse gas emissions and removals because it helps to inform and prioritize inventory improvements. Recognizing the benefit of conducting an uncertainty analysis, the UNFCCC reporting guidelines follow the recommendations of the *2006 IPCC Guidelines* (IPCC 2006), Volume 1, Chapter 3 and require that countries provide single estimates of uncertainty for source and sink categories. In addition to quantitative uncertainty assessments, a qualitative discussion of uncertainty is presented for each source and sink category identifying specific factors affecting the uncertainty surrounding the estimates provided in accordance with UNFCCC reporting guidelines. Some of the current estimates, such as those for CO_2 emissions from energy-related combustion activities, are considered to have low uncertainties. This is because the amount of CO_2 emitted from energy-related combustion activities is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel, and for the United States, the uncertainties associated with estimating those factors is relatively small. For some other categories of emissions, however, inherent variability or a lack of data increases the uncertainty or systematic error associated with the estimates presented. Finally, an analysis is conducted to assess uncertainties associated with the overall emissions, sinks and trends estimates. The overall uncertainty surrounding total net greenhouse gas emissions is estimated to be -5 to +6 percent in 1990 and -5 to +6 percent in 2020. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -2 to +5 percent in 1990 and -2 to +5 percent in 2020.

1. Introduction

This report presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and sinks for the years 1990 through 2020. A summary of these estimates is provided in Table 2-1 and Table 2-2 by gas and source category in the Trends in Greenhouse Gas Emissions chapter. The emission and sink estimates in these tables are presented on both a full mass basis and on a global warming potential (GWP) weighted basis[1] in order to show the relative contribution of each gas to global average radiative forcing. This report also discusses the methods and data used to calculate these emission estimates.

In 1992, the United States signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."[2,3]

As a signatory to the UNFCCC, consistent with Article 4[4] and decisions at the First, Second, Fifth, and Nineteenth Conference of Parties,[5] the U.S. is committed to submitting a national inventory of anthropogenic sources and sinks of greenhouse gases to the UNFCCC by April 15 of each year. This Inventory provides a national estimate of sources and sinks for the United States, including all states, the District of Columbia and U.S. Territories.[6] The United States views this report, in conjunction with Common Reporting Format (CRF) reporting tables that accompany this report, as an opportunity to fulfill this annual commitment under the UNFCCC. Overall, this Inventory of anthropogenic greenhouse gas emissions and sinks provides a common and consistent mechanism

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[1] More information provided in the Global Warming Potentials section of this chapter on the use of *IPCC Fourth Assessment Report* (AR4) GWP values.

[2] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities (IPCC 2006).

[3] Article 2 of the Framework Convention on Climate Change published by the UNEP/WMO Information Unit on Climate Change (UNEP/WMO 2000). See http://unfccc.int.

[4] Article 4(1)(a) of the United Nations Framework Convention on Climate Change (also identified in Article 12) and subsequent decisions by the Conference of the Parties elaborated the role of Annex I Parties in preparing national inventories. Article 4 states "Parties to the Convention, by ratifying, shall develop, periodically update, publish and make available…national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies…" See http://unfccc.int for more information.

[5] See UNFCCC decisions 3/CP.1, 9/CP.2, 3/CP.5, and 24/CP.19 at https://unfccc.int/documents.

[6] U.S. Territories include American Samoa, Guam, Commonwealth of the Northern Mariana Islands, Puerto Rico, U.S. Virgin Islands, and other outlying U.S. Pacific Islands which are not permanently inhabited such as Wake Island. See https://www.usgs.gov/faqs/how-are-us-states-territories-and-commonwealths-designated-geographic-names-information-system?qt-news_science_products=0#qt-news_science_products. See more information on completeness in Section 1.8.

through which Parties to the UNFCCC can compare the relative contribution of individual sources, gases, and nations to climate change. The structure of this report is consistent with the current UNFCCC Guidelines on Annual Inventories (UNFCCC 2014) for Parties included in Annex I of the Convention.

In 1988, preceding the creation of the UNFCCC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) jointly established the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation (IPCC 2021). Under Working Group 1 of the IPCC, nearly 140 scientists and national experts from more than thirty countries collaborated in the creation of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) to ensure that the emission inventories submitted to the UNFCCC are consistent and comparable between nations. The *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and the *IPCC Good Practice Guidance for Land Use, Land-Use Change, and Forestry* further expanded upon the methodologies in the *Revised 1996 IPCC Guidelines*. In 2006, the IPCC accepted the *2006 Guidelines for National Greenhouse Gas Inventories* at its Twenty-Fifth Session (Mauritius, April 2006). The *2006 IPCC Guidelines* built upon the previous bodies of work and include new sources and gases, "…as well as updates to the previously published methods whenever scientific and technical knowledge have improved since the previous guidelines were issued." The UNFCCC adopted the *2006 IPCC Guidelines* as the standard methodological approach for Annex I countries and encouraged countries to gain experience in using the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* at the Nineteenth Conference of the Parties (Warsaw, November 11-23, 2013). The IPCC has recently released the *2019 Refinement to the 2006 IPCC Guideline*s *for National Greenhouse Gas Inventories* to clarify and elaborate on the existing guidance in the *2006 IPCC Guidelines*, along with providing updates to default values of emission factors and other parameters based on updated science. This report applies both the *2013 Supplement* and updated guidance in the *2019 Refinement* to improve accuracy and completeness of the Inventory. For more information on specific uses see Section 1.4 of this chapter on Methodology and Data Sources.

Box 1-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the UNFCCC requirement under Article 4.1 and decision 24/CP.19 to develop and submit annual national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and where appropriate, its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in this Inventory does not preclude alternative examinations, but rather this Inventory presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP).[7] The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject carbon dioxide (CO_2) underground for sequestration or other reasons and requires reporting by over 8,000 sources or suppliers

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[7] On October 30, 2009 the EPA promulgated a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emissions sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

in 41 industrial categories.[8] Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. Facilities in most source categories subject to GHGRP began reporting for the 2010 reporting year while additional types of industrial operations began reporting for reporting year 2011. While the GHGRP does not provide full coverage of total annual U.S. greenhouse gas emissions and sinks (e.g., the GHGRP excludes emissions from the agricultural, land use, and forestry sectors), it is an important input to the calculations of national-level emissions in the Inventory.

Data presented in this Inventory report and EPA's GHGRP are complementary. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information such as activity data and emission factors that can improve and refine national emission estimates and trends over time. Methodologies used in EPA's GHGRP are consistent with the *2006 IPCC Guidelines* (e.g., higher tier methods). GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing the application of QA/QC procedures and assessment of uncertainties. EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory consistent with IPCC methodological guidance. See Annex 9 for more information on specific uses of GHGRP data in the Inventory (e.g., natural gas systems).

1.1 Background Information

Science

For over the past 200 years, the burning of fossil fuels such as coal and oil, along with deforestation, land-use changes, and other activities have caused the concentrations of heat-trapping "greenhouse gases" to increase significantly in our atmosphere (IPCC 2021). These gases in the atmosphere absorb some of the energy being radiated from the surface of the Earth that would otherwise be lost to space, essentially acting like a blanket that makes the Earth's surface warmer than it would be otherwise.

Greenhouse gases are necessary to life as we know it. Without greenhouse gases to create the natural heat-trapping properties of the atmosphere, the planet's surface would be about 60 degrees Fahrenheit cooler than present (USGCRP 2017). Carbon dioxide is also necessary for plant growth. With emissions from biological and geological sources, there is a natural level of greenhouse gases that is maintained in the atmosphere. Human emissions of greenhouse gases and subsequent changes in atmospheric concentrations alter the balance of energy transfers between space and the earth system (IPCC 2021). A gauge of these changes is called radiative forcing, which is a measure of a substance's total net effect on the global energy balance for which a positive number represents a warming effect and a negative number represents a cooling effect (IPCC 2021). IPCC concluded in its most recent scientific assessment report that it is "unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC 2021).

As concentrations of greenhouse gases continue to increase in from man-made sources, the Earth's temperature is climbing above past levels. The Earth's average land and ocean surface temperature has increased by about 2.0 degrees Fahrenheit from the 1850 to 1900 period to the decade of 2011 to 2020 (IPCC 2021). The last four decades have each been the warmest decade successively at the Earth's surface since at least 1850 (IPCC 2021). Other aspects of the climate are also changing, such as rainfall patterns, snow and ice cover, and sea level. If greenhouse gas concentrations continue to increase, climate models predict that the average temperature at the Earth's surface is likely to increase by up to 8.3 degrees Fahrenheit above 2011 to 2020 levels by the end of this century,

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[8] See http://www.epa.gov/ghgreporting and http://ghgdata.epa.gov/ghgp/main.do.

depending on future emissions and the responsiveness of the climate system (IPCC 2021), though the lowest emission scenario would limit future warming to an additional 0.5 degrees (best estimate).

For further information on greenhouse gases, radiative forcing, and implications for climate change, see the recent scientific assessment reports from the IPCC,[9] the U.S. Global Change Research Program (USGCRP),[10] and the National Academies of Sciences, Engineering, and Medicine (NAS).[11]

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 2021).

Naturally occurring greenhouse gases include water vapor, CO_2, CH_4, N_2O, and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty. Consequently, Parties to the UNFCCC are not required to include these gases in national greenhouse gas inventories.[12] Some other fluorine-containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several other substances that influence the global radiation budget but are short-lived and therefore not well-mixed, leading to spatially variable radiative forcing effects. These substances include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (VOCs, including CH_4) and nitrogen oxides (NO_x), in the presence of ultraviolet light (sunlight).

Aerosols are extremely small particles or liquid droplets suspended in the Earth's atmosphere that are often composed of sulfur compounds, carbonaceous combustion products (e.g., black carbon), crustal materials (e.g., dust) and other human-induced pollutants. They can affect the absorptive characteristics of the atmosphere (e.g., scattering incoming sunlight away from the Earth's surface, or, in the case of black carbon, absorb sunlight) and can play a role in affecting cloud formation and lifetime, as well as the radiative forcing of clouds and precipitation patterns.

Carbon dioxide, CH_4, and N_2O are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities (such as fossil fuel combustion, cement production, land-use, land-use change, and forestry, agriculture, or waste management), however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass.

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[9] See https://www.ipcc.ch/report/ar6/wg1/.

[10] See https://nca2018.globalchange.gov/.

[11] See https://www.nationalacademies.org/topics/climate.

[12] Emissions estimates of CFCs, HCFCs, halons and other ozone-depleting substances are included in this document for informational purposes.

Such processes, except when directly or indirectly perturbed out of equilibrium by anthropogenic activities, generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1-1.

Table 1-1: Global Atmospheric Concentration, Rate of Concentration Change, and Atmospheric Lifetime of Selected Greenhouse Gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6	CF_4
Pre-industrial atmospheric concentration	280 ppm	0.730 ppm	0.270 ppm	0 ppt	40 ppt
Atmospheric concentration	414 ppm[a]	1.879 ppm[b]	0.333 ppm[c]	10.27 ppt[d]	85.5 ppt[e]
Rate of concentration change	2.32 ppm/yr[f]	7.91 ppb/yr[f,g]	0.97 ppb/yr[f]	0.32 ppt/yr[f]	0.81 ppt/yr[f]
Atmospheric lifetime (years)	See footnote[h]	11.8	109[i]	About 1,000[j]	50,000

[a] The atmospheric CO_2 concentration is the 2020 annual average at the Mauna Loa, HI station (NOAA/ESRL 2021a). The global atmospheric CO_2 concentration, computed using an average of sampling sites across the world, was 412 ppm in 2019.

[b] The values presented are global 2020 annual average mole fractions (NOAA/ESRL 2021b).

[c] The values presented are global 2020 annual average mole fractions (NOAA/ESRL 2021c).

[d] The values presented are global 2020 annual average mole fractions (NOAA/ESRL 2021d).

[e] The 2019 CF_4 global mean atmospheric concentration is from the Advanced Global Atmospheric Gases Experiment (IPCC 2021).

[f] The rate of concentration change for CO_2 is an average of the rates from 2007 through 2020 and has fluctuated between 1.5 to 3.0 ppm per year over this period (NOAA/ESRL 2021a). The rate of concentration change for CH_4, N_2O, and SF_6, is the average rate of change between 2007 and 2020 (NOAA/ESRL 2021b; NOAA/ESRL 2021c; NOAA/ESRL 2021d). The rate of concentration change for CF_4 is the average rate of change between 2011 and 2019 (IPCC 2021).

[g] The growth rate for atmospheric CH_4 decreased from over 10 ppb/year in the 1980s to nearly zero in the early 2000s; recently, the growth rate has been about 7.91 ppb/year (NOAA/ESRL 2021b).

[h] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[i] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

[j] The lifetime for SF_6 was revised from 3,200 years to about 1,000 years based on recent studies (IPCC 2021).

Source: Pre-industrial atmospheric concentrations and atmospheric lifetimes for CH_4, N_2O, SF_6, and CF_4 are from IPCC (2021).

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of GWPs, which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Water vapor is the largest contributor to the natural greenhouse effect. Water vapor is fundamentally different from other greenhouse gases in that it can condense and rain out when it reaches high concentrations, and the total amount of water vapor in the atmosphere is in part a function of the Earth's temperature. While some human activities such as evaporation from irrigated crops or power plant cooling release water vapor into the air, these activities have been determined to have a negligible effect on global climate (IPCC 2021). The lifetime of water vapor in the troposphere is on the order of 10 days. Water vapor can also contribute to cloud formation, and clouds can have both warming and cooling effects by either trapping or reflecting heat. Because of the relationship between water vapor levels and temperature, water vapor and clouds serve as a feedback to climate change, such that for any given increase in other greenhouse gases, the total warming is greater than would happen in the absence of water vapor. Aircraft emissions of water vapor can create contrails, which may also develop into contrail-induced cirrus clouds, with complex regional and temporal net radiative forcing effects that currently have a low level of scientific certainty (IPCC 2021).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric CO_2 is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 416 ppmv in 2020, a 49 percent increase (IPCC 2021; NOAA/ESRL 2021a).[13,14] The IPCC states that "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities" (IPCC 2021). The predominant source of anthropogenic CO_2 emissions is the combustion of fossil fuels. Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of CO_2. In its *Sixth Assessment Report*, the IPCC determined that of the 2.0 degrees of observed warming, the best estimate is that 1.9 degrees of that are due to human influence, with elevated CO_2 concentrations being the most important contributor to that warming (IPCC 2021).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes and treatment of wastewater. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of CH_4 have increased by about 157 percent since 1750, from a pre-industrial value of about 730 ppb to 1,879 ppb in 2020[15] although the rate of increase decreased to near zero in the early 2000s, and has recently increased again to about 7.91 ppb/year. The IPCC has estimated that about half of the current CH_4 flux to the atmosphere (and the entirety of the increase in concentration) is anthropogenic, from human activities such as agriculture, fossil fuel production and use, and waste disposal (IPCC 2021).

Methane is primarily removed from the atmosphere through a reaction with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with chlorine in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of CH_4 reduce the concentration of OH, a feedback that increases the atmospheric lifetime of CH_4 (IPCC 2021). Methane's reactions in the atmosphere also lead to production of tropospheric ozone and stratospheric water vapor, both of which also contribute to climate change. Tropospheric ozone also has negative effects on human health and plant productivity.

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially production of nitrogen-fixing crops and forages, the use of synthetic and manure fertilizers, and manure deposition by livestock; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste incineration; and biomass burning. The atmospheric concentration of N_2O has increased by 23 percent since 1750, from a pre-industrial value of about 270 ppb to 333 ppb in 2020,[16] a concentration that has not been exceeded during at least the last 800 thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere (IPCC 2021).

Ozone (O_3). Ozone is present in both the upper stratosphere,[17] where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[18] where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as CFCs, have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of

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[13] The pre-industrial period is considered as the time preceding the year 1750 (IPCC 2013).

[14] Carbon dioxide concentrations during the last 1,000 years of the pre-industrial period (i.e., 750 to 1750), a time of relative climate stability, fluctuated by about ±10 ppmv around 280 ppmv (IPCC 2013).

[15] This value is the global 2020 annual average mole fraction (NOAA/ESRL 2021b).

[16] This value is the global 2020 annual average (NOAA/ESRL 2021c).

[17] The stratosphere is the layer from the troposphere up to roughly 50 kilometers. In the lower regions the temperature is nearly constant but in the upper layer the temperature increases rapidly because of sunlight absorption by the ozone layer. The ozone-layer is the part of the stratosphere from 19 kilometers up to 48 kilometers where the concentration of ozone reaches up to 10 parts per million.

[18] The troposphere is the layer from the ground up to 11 kilometers near the poles and up to 16 kilometers in equatorial regions (i.e., the lowest layer of the atmosphere where people live). It contains roughly 80 percent of the mass of all gases in the atmosphere and is the site for most weather processes, including most of the water vapor and clouds.

anthropogenic emissions of chlorine and bromine compounds (IPCC 2021). The depletion of stratospheric ozone and its radiative forcing remained relatively unchanged since 2000 for the last two decades and is starting to decline; recovery is expected to occur shortly after the middle of the twenty-first century (WMO/UNEP 2018).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds (including CH_4) mixing with NO_x in the presence of sunlight. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable (IPCC 2021).

Halocarbons, Sulfur Hexafluoride, and Nitrogen Trifluoride. Halocarbons are, for the most part, man-made chemicals that have direct radiative forcing effects and could also have an indirect effect. Halocarbons that contain chlorine (CFCs, HCFCs, methyl chloroform, and carbon tetrachloride) and bromine (halons, methyl bromide, and hydrobromofluorocarbons) result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although most CFCs and HCFCs are potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which itself is a greenhouse gas but which also shields the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5 countries, including the United States,[19] beginning in 1996, and then followed by intermediate requirements and a complete phase-out by the year 2030. While ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC, they are reported in this Inventory under Annex 6.2 for informational purposes.

Hydrofluorocarbons, PFCs, SF_6, and NF_3 are not ozone depleting substances. The most common HFCs are, however, powerful greenhouse gases. Hydrofluorocarbons are primarily used as replacements for ozone depleting substances but also emitted as a byproduct of the HCFC-22 (chlorodifluoromethane) manufacturing process. Currently, they have a small aggregate radiative forcing impact, but it is anticipated that without further controls their contribution to overall radiative forcing will increase (IPCC 2013). On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption of HFCs (i.e., production plus import, minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions, which will lead to lower HFC emissions over time. Perfluorocarbons, SF_6, and NF_3 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs, SF_6, and NF_3 is also small, but they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2021).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect. Warming effects can occur due to reactions leading to the formation of ozone in the troposphere, but cooling effects can occur due to the role of NO_x as a precursor to nitrate particles (i.e., aerosols) and due to destruction of

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[19] Article 5 of the Montreal Protocol covers several groups of countries, especially developing countries, with low consumption rates of ozone depleting substances. Developing countries with per capita consumption of less than 0.3 kg of certain ozone depleting substances (weighted by their ozone depleting potential) receive financial assistance and a grace period of ten additional years in the phase-out of ozone depleting substances.

stratospheric ozone when emitted from very high-altitude aircraft.[20] Additionally, NO_x emissions are also likely to decrease CH_4 concentrations, thus having a negative radiative forcing effect (IPCC 2021). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning (both natural and anthropogenic fires) fuel combustion, and, in the stratosphere, from the photo-degradation of N_2O. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Non-methane Volatile Organic Compounds (NMVOCs). Non-methane volatile organic compounds include substances such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere that are either directly emitted into or are created through chemical reactions in the Earth's atmosphere. Aerosols or their chemical precursors can be emitted by natural events such as dust storms, biogenic or volcanic activity, or by anthropogenic processes such as transportation, coal combustion, cement manufacturing, waste incineration, or biomass burning. Various categories of aerosols exist from both natural and anthropogenic sources, such as soil dust, sea salt, biogenic aerosols, sulfates, nitrates, volcanic aerosols, industrial dust, and carbonaceous[21] aerosols (e.g., black carbon, organic carbon). Aerosols can be removed from the atmosphere relatively rapidly by precipitation or through more complex processes under dry conditions.

Aerosols affect radiative forcing differently than greenhouse gases. Their radiative effects occur through direct and indirect mechanisms: directly by scattering and absorbing solar radiation (and to a lesser extent scattering, absorption, and emission of terrestrial radiation); and indirectly by increasing cloud droplets and ice crystals that modify the formation, precipitation efficiency, and radiative properties of clouds (IPCC 2021). Despite advances in understanding of cloud-aerosol interactions, the contribution of aerosols to radiative forcing are difficult to quantify because aerosols generally have short atmospheric lifetimes, and have number concentrations, size distributions, and compositions that vary regionally, spatially, and temporally (IPCC 2021).

The net effect of aerosols on the Earth's radiative forcing is believed to be negative (i.e., net cooling effect on the climate). In fact, aerosols contributed a cooling influence of up to 1.4 degrees, offsetting a substantial portion of greenhouse gas warming (IPCC 2021). Because aerosols remain in the atmosphere for only days to weeks, their concentrations respond rapidly to changes in emissions.[22] Not all aerosols have a cooling effect. Current research suggests that another constituent of aerosols, black carbon, has a positive radiative forcing by heating the Earth's atmosphere and causing surface warming when deposited on ice and snow (IPCC 2021). Black carbon also influences cloud development, but the direction and magnitude of this forcing is an area of active research.

Global Warming Potentials

A global warming potential is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas (see Table 1-2). It is defined as the accumulated radiative forcing within a specific time horizon caused by emitting 1 kilogram (kg) of the gas, relative to that of the reference gas CO_2 (IPCC 2021). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The reference

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[20] NO_x emissions injected higher in the stratosphere, primarily from fuel combustion emissions from high altitude supersonic aircraft, can lead to stratospheric ozone depletion.

[21] Carbonaceous aerosols are aerosols that are comprised mainly of organic substances and forms of black carbon (or soot) (IPCC 2013).

[22] Volcanic activity can inject significant quantities of aerosol producing sulfur dioxide and other sulfur compounds into the stratosphere, which can result in a longer lasting negative forcing effect (i.e., a few years) (IPCC 2013).

gas used is CO_2, and therefore GWP-weighted emissions are measured in million metric tons of CO_2 equivalent (MMT CO_2 Eq.).[23] The relationship between kilotons (kt) of a gas and MMT CO_2 Eq. can be expressed as follows:

Equation 1-1: Calculating CO_2 Equivalent Emissions

$$\mathbf{MMT\ CO_2\ Eq.} = (\mathbf{kt\ of\ gas}) \times (\mathbf{GWP}) \times \left(\frac{\mathbf{MMT}}{\mathbf{1{,}000\ kt}}\right)$$

where,

MMT CO_2 Eq. = Million metric tons of CO_2 equivalent
kt = kilotons (equivalent to a thousand metric tons)
GWP = Global warming potential
MMT = Million metric tons

GWP values allow for a comparison of the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±40 percent. Parties to the UNFCCC are required to use GWPs based upon a 100-year time horizon from the *IPCC Fourth Assessment Report* (AR4), although other time horizon values are available.

> *…the global warming potential values used by Parties included in Annex I to the Convention (Annex I Parties) to calculate the carbon dioxide equivalence of anthropogenic emissions by sources and removals by sinks of greenhouse gases shall be those listed in the column entitled "Global warming potential for given time horizon" in table 2.14 of the errata to the contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, based on the effects of greenhouse gases over a 100-year time horizon...*[24]

All estimates are provided throughout the report in both MMT CO_2 equivalents and unweighted units. The UNFCCC will require countries to shift to use of *IPCC Fifth Assessment Report* (AR5) (IPCC 2013) 100-year GWP values in 2024, when countries submit their first reports using updated reporting guidelines under the Paris Agreement.[25] A comparison of emission estimates using the 100-year AR4 GWP values versus the AR5 GWP values and the *IPCC Sixth Assessment Report (AR6)* (IPCC 2021) is outlined in Box 1-2 below and, in more detail, in Annex 6.1 of this report.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, ozone precursors (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and carbonaceous particles), however, vary regionally, and consequently it is difficult to quantify their global radiative forcing impacts. Parties to the UNFCCC have not agreed upon GWP values for these gases that are short-lived and spatially inhomogeneous in the atmosphere.

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[23] Carbon comprises 12/44^{ths} of carbon dioxide by weight.

[24] Framework Convention on Climate Change; Available online at: http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf; 31 January 2014; Report of the Conference of the Parties at its nineteenth session; held in Warsaw from 11 to 23 November 2013; Addendum; Part two: Action taken by the Conference of the Parties at its nineteenth session; Decision 24/CP.19; Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention; p. 2. (UNFCCC 2014).

[25] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement

Table 1-2: Global Warming Potentials and Atmospheric Lifetimes (Years) Used in this Report

Gas	Atmospheric Lifetime	GWP[a]
CO_2	See footnote[b]	1
CH_4[c]	12	25
N_2O	114	298
HFC-23	270	14,800
HFC-32	4.9	675
HFC-41[d]	3.7	92
HFC-125	29	3,500
HFC-134a	14	1,430
HFC-143a	52	4,470
HFC-152a	1.4	124
HFC-227ea	34.2	3,220
HFC-236fa	240	9,810
CF_4	50,000	7,390
C_2F_6	10,000	12,200
C_3F_8	2,600	8,830
c-C_4F_8	3,200	10,300
SF_6	3,200	22,800
NF_3	740	17,200
Other Fluorinated Gases		See Annex 6

[a] 100-year time horizon.

[b] For a given amount of CO_2 emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, some fraction of the atmospheric increase will only slowly decrease over a number of years, and a small portion of the increase will remain for many centuries or more.

[c] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

[d] See Table A-1 of 40 CFR Part 98

Source: IPCC (2013).

Box 1-2: The *IPCC Sixth Assessment Report* and Global Warming Potentials

In 2021, the IPCC published its *Sixth Assessment Report* (AR6), which updated its comprehensive scientific assessment of climate change. Within the AR6 report, the GWP values of gases were revised relative to previous IPCC reports, namely the *IPCC Second Assessment Report* (SAR) (IPCC 1996), the *IPCC Third Assessment Report* (TAR) (IPCC 2001), the *IPCC Fourth Assessment Report* (AR4) (IPCC 2007), and the *IPCC Fifth Assessment Report* (AR5) (IPCC 2014). Although the AR4 GWP values are used throughout this report, consistent with UNFCCC reporting requirements, it is straight-forward to review the changes to the GWP values and their impact on estimates of the total GWP-weighted emissions of the United States. In the AR6, the IPCC used more recent estimates of the atmospheric lifetimes and radiative efficiencies of some gases and updated background concentrations. The AR6 now includes climate-carbon feedback effects for non-CO_2 gases, improving the consistency between treatment of CO_2 and non-CO_2 gases. Indirect effects of gases on other atmospheric constituents (such as the effect of methane on ozone) have also been updated to match more recent science.

Table 1-3 presents the new GWP values, relative to those presented in the AR4 and AR5, using the 100-year time horizon common to UNFCCC reporting. For consistency with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using AR4 100-year GWP values, as required by the 2013 revision to the UNFCCC reporting guidelines for national inventories.[26] Updated reporting guidelines under the Paris Agreement which require the United States and other countries to shift to use of *IPCC Fifth Assessment Report* (AR5) (IPCC 2013) 100-year GWP values (without feedbacks) take effect for national inventory reporting in 2024.[27] All estimates provided throughout this report are also presented in unweighted units. For informational purposes, emission estimates that use 100-year GWPs from other recent IPCC Assessment Reports are presented in detail in Annex 6.1 of this report.

Table 1-3: Comparison of 100-Year GWP values

	100-Year GWP Values				Comparisons to AR4		
Gas	**AR4**	**AR5[a]**	**AR5 with feedbacks[b]**	**AR6[c]**	**AR5**	**AR5 with feedbacks[b]**	**AR6[c]**
CO_2	1	1	1	1	NC	NC	NC
CH_4[d]	25	28	34	27	3	9	2
N_2O	298	265	298	273	(33)	NC	(25)
HFC-23	14,800	12,400	13,856	14,600	(2,400)	(944)	(200)
HFC-32	675	677	817	771	2	142	96
HFC-41	92	116	NA	135	24	NA	43
HFC-125	3,500	3,170	3,691	3,740	(330)	191	240
HFC-134a	1,430	1,300	1,549	1,526	(130)	119	96
HFC-143a	4,470	4,800	5,508	5,810	330	1,038	1,340
HFC-152a	124	138	167	164	14	43	40
HFC-227ea	3,220	3,350	3,860	3,600	130	640	380
HFC-236fa	9,810	8,060	8,998	8,690	(1,750)	(812)	(1,120)
CF_4	7,390	6,630	7,349	7,380	(760)	(41)	(10)
C_2F_6	12,200	11,100	12,340	12,400	(1,100)	140	200
C_3F_8	8,830	8,900	9,878	9,290	70	(1,048)	460
c-C_4F_8	10,300	9,540	10,592	10,200	(760)	292	(100)
SF_6	22,800	23,500	26,087	25,200	700	3,287	2,400
NF_3	17,200	16,100	17,885	17,400	(1,100)	685	200

NA (Not Applicable)

NC (No Change)

[a] The GWPs presented here are the ones most consistent with the methodology used in the AR4 report.

[b] The GWP values presented here from the AR5 report include climate-carbon feedbacks for the non-CO_2 gases in order to be consistent with the approach used in calculating the CO_2 lifetime.

[c] The 100-year GWPs from AR6 are prepublication values based on the Working Group 1 report published in August 2021. As the report is finalized for full publication, in the final editing process, these values may be updated in corrigenda and EPA will update this analysis to reflect the final values.

[d] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. Including the indirect effect due to the production of CO_2 resulting from methane oxidation would lead to an increase in AR5 methane GWP values by 2 for fossil methane and is not shown in this table.

Note: Parentheses indicate negative values.

Sources: IPCC (2013), IPCC (2007), IPCC (2001), IPCC (1996).

1.2 National Inventory Arrangements

The U.S. Environmental Protection Agency (EPA), in cooperation with other U.S. government agencies, prepares the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. A wide range of agencies and individuals are involved in

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[26] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

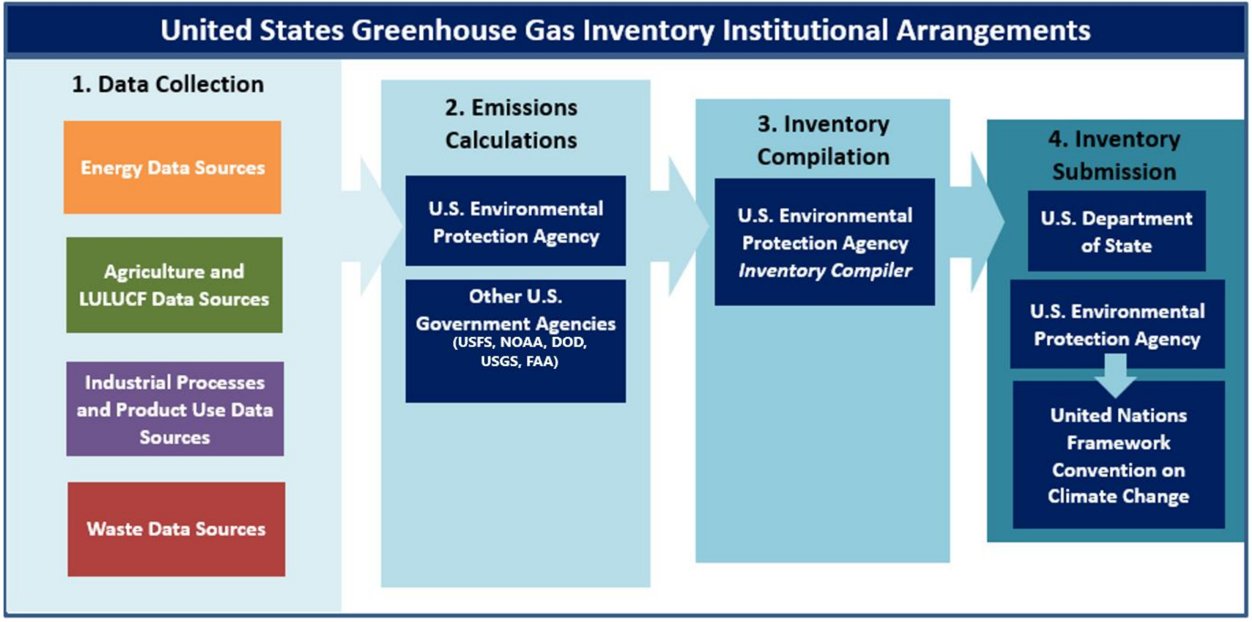
[27] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

supplying data to, planning methodological approaches and improvements, reviewing, or preparing portions of the U.S. Inventory—including federal and state government authorities, research and academic institutions, industry associations, and private consultants.

Within EPA, the Office of Atmospheric Programs (OAP) is the lead office responsible for the emission calculations provided in the Inventory, as well as the completion of the National Inventory Report and the Common Reporting Format (CRF) tables. EPA's Office of Transportation and Air Quality (OTAQ) and Office of Research and Development (ORD) are also involved in calculating emissions and removals for the Inventory. The U.S. Department of State serves as the overall national focal point to the UNFCCC, and EPA's OAP serves as the National Inventory Focal Point for this report, including responding to technical questions and comments on the U.S. Inventory. EPA staff coordinate the annual methodological choice, activity data collection, emission calculations, QA/QC processes, and improvement planning at the individual source and sink category level. EPA, the inventory coordinator, compiles the entire Inventory into the proper reporting format for submission to the UNFCCC, and is responsible for the synthesis of information and for the consistent application of cross-cutting IPCC good practice across the Inventory.

Several other government agencies contribute to the collection and analysis of the underlying activity data used in the Inventory calculations via formal (e.g., interagency agreements) and informal relationships, in addition to the calculation of estimates integrated in the report (e.g., U.S. Department of Agriculture's U.S. Forest Service and Agricultural Service, National Oceanic and Atmospheric Administration, Federal Aviation Administration, and Department of Defense). Other U.S. agencies provide official data for use in the Inventory. The U.S. Department of Energy's Energy Information Administration provides national fuel consumption data and the U.S. Department of Defense provides data on military fuel consumption and use of bunker fuels. Other U.S. agencies providing activity data for use in EPA's emission calculations include: the U.S. Department of Agriculture, National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Federal Highway Administration, the Department of Transportation, the Bureau of Transportation Statistics, the Department of Commerce, and the Federal Aviation Administration. Academic and research centers also provide activity data and calculations to EPA, as well as individual companies participating in voluntary outreach efforts with EPA. Finally, EPA as the National Inventory Focal Point, in coordination with the U.S. Department of State, officially submits the Inventory to the UNFCCC each April.

Figure 1-1: National Inventory Arrangements and Process Diagram



Overview of Inventory Data Sources by Source and Sink Category

Energy	Agriculture and LULUCF	IPPU	Waste
Energy Information Administration	EPA Office of Land and Emergency Management	EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Greenhouse Gas Reporting Program (GHGRP)
U.S. Department of Commerce – Bureau of the Census	Alaska Department of Natural Resources	American Chemistry Council (ACC)	EPA Office of Land and Emergency Management
U.S. Department of Defense – Defense Logistics Agency	National Oceanic and Atmospheric Administration (NOAA)	U.S. Geological Survey (USGS) National Minerals Information Center	Data from research studies, trade publications, and industry associations
Federal Highway Administration	Association of American Plant Food Control Officials (AAPFCO)	American Iron and Steel Institute (AISI)	
EPA Acid Rain Program	U.S. Census Bureau	U.S. Aluminum Association	
EPA Office of Transportation and Air Quality MOVES Model	U.S. Department of Agriculture (USDA) Animal and Plant Health Inspection Service (APHIS)	U.S. International Trade Commission (USITC)	
EPA Greenhouse Gas Reporting Program (GHGRP)	EPA Office of Research and Development	Air-Conditioning, Heating, and Refrigeration Institute	
U.S. Department of Labor – Mine Safety and Health Administration	USDA National Agricultural Statistics Service and Agricultural Research Service	Data from other U.S. government agencies, research studies, trade publications, and industry associations	
American Association of Railroads	USDA U.S. Forest Service Forest Inventory and Analysis Program		
American Public Transportation Association	USDA Natural Resource Conservation Service (NRCS)		
U.S. Department of Homeland Security	USDA Economic Research Service (ERS)		
U.S. Department of Energy and its National Laboratories	USDA Farm Service Agency (FSA)		
Federal Aviation Administration	U.S. Geological Survey (USGS)		
U.S. Department of Transportation & Bureau of Transportation Statistics	U.S. Department of the Interior (DOI), Bureau of Land Management (BLM)		
Data from research studies, trade publications, and industry associations	Data from research studies, trade publications, and industry associations		

Note: This table is not an exhaustive list of all data sources.

1.3 Inventory Process

This section describes EPA's approach to preparing the annual U.S. Inventory, which consists of a National Inventory Report (NIR) and Common Reporting Format (CRF) tables. The inventory coordinator at EPA, with support from the cross-cutting compilation staff, is responsible for aggregating all emission and removal estimates, conducting the overall uncertainty analysis of Inventory emissions and trends over time, and ensuring consistency and quality throughout the NIR and CRF tables. Emission calculations, including associated uncertainty analysis for individual sources and/or sink categories are the responsibility of individual source and sink category leads, who are most familiar with each category, underlying data, and the unique national circumstances relevant to its emissions or removals profile. Using IPCC good practice guidance, the individual leads determine the most appropriate methodology and collect the best activity data to use in the emission and removal calculations, based upon their expertise in the source or sink category, as well as coordinating with researchers and contractors familiar with the sources. Each year, the coordinator oversees a multi-stage process for collecting information from each individual source and sink category lead to compile all information and data for the Inventory.

Methodology Development, Data Collection, and Emissions and Sink Estimation

Source and sink category leads at EPA collect input data and, as necessary, evaluate or develop the estimation methodology for the individual source and/or sink categories. Because EPA has been preparing the Inventory for many years, for most source and sink categories, the methodology for the previous year is applied to the new "current" year of the Inventory, and inventory analysts collect any new data or update data that have changed from the previous year. If estimates for a new source or sink category are being developed for the first time, or if the methodology is changing for an existing category (e.g., the United States is implementing improvement efforts to apply a higher tiered approach for that category), then the source and/or sink category lead will develop and implement the new or refined methodology, gather the most appropriate activity data and emission factors (or in some cases direct emission measurements) for the entire time series, and conduct any further category-specific review with involvement of relevant experts from industry, government, and universities (see Box ES-3 on EPA's approach to recalculations).

Once the methodology is in place and the data are collected, the individual source and sink category leads calculate emission and removal estimates. The individual leads then update or create the relevant text and accompanying annexes for the Inventory. Source and sink category leads are also responsible for completing the relevant sectoral background tables of the CRF, conducting quality assurance and quality control (QA/QC) checks, and category-level uncertainty analyses.

The treatment of confidential business information (CBI) in the Inventory is based on EPA internal guidelines, as well as regulations[28] applicable to the data used. EPA has specific procedures in place to safeguard CBI during the inventory compilation process. When information derived from CBI data is used for development of inventory calculations, EPA procedures ensure that these confidential data are sufficiently aggregated to protect confidentiality while still providing useful information for analysis. For example, within the Energy and Industrial Processes and Product Use (IPPU) sectors, EPA has used aggregated facility-level data from the Greenhouse Gas Reporting Program (GHGRP) to develop, inform, and/or quality-assure U.S. emission estimates. In 2014, EPA's GHGRP, with industry engagement, compiled criteria that would be used for aggregating its confidential data to shield the underlying CBI from public disclosure.[29] In the Inventory, EPA is publishing only data values that meet the GHGRP aggregation criteria.[30] Specific uses of aggregated facility-level data are described in the respective methodological sections within those chapters. In addition, EPA uses historical data reported voluntarily to EPA via various voluntary initiatives with U.S. industry (e.g., EPA Voluntary Aluminum Industrial Partnership (VAIP)) and follows guidelines established under the voluntary programs for managing CBI.

Data Compilation and Archiving

The inventory coordinator at EPA with support from the data/document manager collects the source and sink categories' descriptive text and annexes, and also aggregates the emission and removal estimates into a summary

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[28] 40 CFR part 2, Subpart B titled "Confidentiality of Business Information" which is the regulation establishing rules governing handling of data entitled to confidentiality treatment. See https://www.ecfr.gov/cgi-bin/text-idx?SID=a764235c9eadf9afe05fe04c07a28939&mc=true&node=sp40.1.2.b&rgn=div6.

[29] Federal Register Notice on "Greenhouse Gas Reporting Program: Publication of Aggregated Greenhouse Gas Data." See pp. 79 and 110 of notice at https://www.gpo.gov/fdsys/pkg/FR-2014-06-09/pdf/2014-13425.pdf.

[30] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

data file that links the individual source and sink category data files together. This summary data file contains all of the essential data in one central location, in formats commonly used in the Inventory document. In addition to the data from each source and sink category, national trend and related data are also gathered in the summary sheet for use in the Executive Summary, Introduction, and Trends sections of the Inventory report. Similarly, the recalculation analysis and key category analysis is completed in a separate data file. The uncertainty estimates for each source and sink category are also aggregated into uncertainty summary data files that are used to conduct the overall Inventory uncertainty analysis (see Section 1.7). Microsoft SharePoint, kept on a central server at EPA under the jurisdiction of the inventory coordinator, provides a platform for the efficient storage, sharing, and archiving of electronic files.

National Inventory Report Preparation

The NIR is compiled from the sections developed by each individual source or sink category lead. In addition, the inventory coordinator prepares a brief overview of each chapter that summarizes the emissions from all sources discussed in the chapters. The inventory coordinator then carries out a key category analysis for the Inventory, consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, and in accordance with the reporting requirements of the UNFCCC. Also at this time, the Introduction, Executive Summary, and Trends in Greenhouse Gas Emissions chapters are drafted, to reflect the trends for the most recent year of the current Inventory. The analysis of trends necessitates gathering supplemental data, including weather and temperature conditions, economic activity and gross domestic product, population, atmospheric conditions, and the annual consumption of electricity, energy, and fossil fuels. Changes in these data are used to explain the trends observed in greenhouse gas emissions in the United States. Furthermore, specific factors that affect individual sectors are researched and discussed. Many of the factors that affect emissions are included in the Inventory document as separate analyses or side discussions in boxes within the text. Text boxes are also created to examine the data aggregated in different ways than in the remainder of the document, such as a focus on transportation activities or emissions from electricity generation. The document is prepared to match the specification of the UNFCCC reporting guidelines for National Inventory Reports.

Common Reporting Format Table Compilation

The CRF tables are compiled from individual tables completed by each individual source or sink category lead, which contain emissions and/or removals and activity data. The inventory coordinator integrates the category data into the UNFCCC's "CRF Reporter" for the United States, assuring consistency across all sectoral tables. The summary reports for emissions, methods, and emission factors used, the overview tables for completeness of estimates, the recalculation tables, the notation key completion tables, and the emission trends tables are then completed by the inventory coordinator. Internal automated quality checks on the CRF Reporter, as well as reviews by the category leads, are completed for the entire time series of CRF tables before submission.

QA/QC and Uncertainty

QA/QC and uncertainty analyses are guided by the QA/QC and Inventory coordinators, who help maintain the QA/QC plan and the overall uncertainty analysis procedures (see sections on QA/QC and Uncertainty, below). This coordinator works closely with the Inventory coordinator and source and sink category leads to ensure that a consistent QA/QC plan and uncertainty analysis is implemented across all inventory sources. The inventory QA/QC plan, outlined in Section 1.7 and Annex 8, is consistent with the quality assurance procedures outlined by EPA and IPCC good practices. The QA/QC and uncertainty findings also inform overall improvement planning, and specific improvements are noted in the Planned Improvements sections of respective categories. QA processes are outlined below.

Expert, Public, and UNFCCC Reviews

The compilation of the inventory includes a two-stage review process, in addition to international technical expert review following submission of the report. During the first stage (the 30-day Expert Review period), a first draft of sectoral chapters of the document are sent to a select list of technical experts outside of EPA who are not directly involved in preparing estimates. The purpose of the Expert Review is to provide an objective review, encourage feedback on the methodological and data sources used in the current Inventory, especially for sources which have experienced any changes since the previous Inventory.

Once comments are received and addressed, the second stage, or second draft of the document is released for public review by publishing a notice in the U.S. Federal Register and posting the entire draft Inventory document on the EPA website. The Public Review period allows for a 30-day comment period and is open to the entire U.S. public. Comments may require further discussion with experts and/or additional research, and specific Inventory improvements requiring further analysis as a result of comments are noted in the relevant category's Planned Improvement section. EPA publishes responses to comments received during both reviews with the publication of the final report on its website.

Following completion and submission of the report to the UNFCCC, the report also undergoes review by an independent international team of experts for adherence to UNFCCC reporting guidelines and IPCC guidance.[31] Feedback from all review processes that contribute to improving inventory quality over time are described further in Annex 8.

Final Submittal to UNFCCC and Document Publication

After the final revisions to incorporate any comments from the Expert Review and Public Review periods, EPA prepares the final NIR and the accompanying CRF tables for electronic reporting. EPA, as the National Inventory focal point, sends the official submission of the U.S. Inventory to the UNFCCC using the CRF Reporter software, coordinating with the U.S. Department of State, the overall UNFCCC focal point. Concurrently, for timely public access, the report is also published on EPA's website.[32]

1.4 Methodology and Data Sources

Emissions of greenhouse gases from various source and sink categories have been estimated using methodologies that are consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and its supplements and refinements. To a great extent, this report makes use of published official economic and physical statistics for activity data and emission factors. Depending on the emission source category, activity data can include fuel consumption or deliveries, vehicle-miles traveled, raw material processed, etc. Emission factors are factors that relate quantities of emissions to an activity. For more information on data sources see Section 1.2 above, Box 1-1 on use of GHGRP data, and categories' methodology sections for more information on other data sources. In addition to official statistics, the report utilizes findings from academic studies, trade association surveys and statistical reports, along with expert judgment, consistent with the *2006 IPCC Guidelines*.

The methodologies provided in the *2006 IPCC Guidelines* represent foundational methodologies for a variety of source categories, and many of these methodologies continue to be improved and refined as new research and data become available. This report uses the IPCC methodologies when applicable, and supplements them with other available country-specific methodologies and data where possible. For examples, as noted earlier in this chapter, this report does use supplements and refinements to *2006 IPCC Guidelines* in estimating emissions and

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[31] See https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/review-process.

[32] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

removals from coal mining, wastewater, Low Voltage Anode Effects (LVAE) during aluminum production, drained organic soils, and management of wetlands, included flooded lands. Choices made regarding the methodologies and data sources used are provided in conjunction with the discussion of each source category in the main body of the report. Where additional detail is helpful and necessary to explain methodologies and data sources used to estimate emissions, complete documentation is provided in the annexes as indicated in the methodology sections of those respective source categories (e.g., Coastal Wetlands).

1.5 Key Categories

The *2006 IPCC Guidelines* (IPCC 2006) defines a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level, the trend, or the uncertainty in emissions and removals."[33] A key category analysis identifies source or sink categories for focusing efforts to improve overall Inventory quality.

The *2006 IPCC Guidelines* (IPCC 2006) defines several approaches, both quantitative and qualitative, to conduct a key category analysis and identify key categories both in terms of absolute level and trend, along with consideration of uncertainty. This report employs all approaches to identify key categories for the United States. The first approach, Approach 1, identifies significant or key categories without considering uncertainty in its calculations. An Approach 1 level assessment identifies all source and sink categories that cumulatively account for 95 percent of total level, i.e., total emissions (gross) in a given year when assessed in descending order of absolute magnitude. The level analysis was performed twice, including and excluding sources and sinks from the Land Use, Land-Use Change, and Forestry (LULUCF) sector categories. Similarly, an Approach 1 trend analysis can identify categories with trends that differ significantly from overall trends by identifying all source and sink categories that cumulatively account for 95 percent of the sum all the trend assessments (e.g., percent change relative to national trend) when sorted in descending order of absolute magnitude.

The next method, Approach 2, was then implemented to identify any additional key categories not already identified from the Approach 1 level and trend assessments by considering uncertainty. The Approach 2 analysis differs from Approach 1 by incorporating each category's uncertainty assessments (or proxies) in its calculations and was also performed twice, including and excluding LULUCF categories. An Approach 2 level assessment identifies all sources and sink categories that cumulatively account for 90 percent of the sum of all level assessments when sorted in descending order of magnitude. Similarly, an Approach 2 trend analysis can identify categories that whose trends differ significantly from overall trends and also weighting the relative trend difference with the category's uncertainty assessment for 2020.

For 2020, based on the key category analysis, excluding the LULUCF sector and uncertainty, 35 categories accounted for 95 percent of emissions. However, only four categories account for 54 percent of emissions: CO_2 from road transport-related fuel combustion, CO_2 from coal-fired electricity generation, CO_2 from gas fired electricity generation, and CO_2 from gas-fired industrial combustion. When considering uncertainties, additional categories such as CH_4 from abandoned oil and gas wells were also identified as a key category. In the trend analysis, 34 categories were identified as key categories, and when considering uncertainties, 7 additional categories were identified as key. The trend analysis shows that HFC and PFC emissions from Substitutes of Ozone Depleting Substances, in addition to CO_2 from coal-fired electricity generation and CO_2 from gas fired electricity generation, and CO_2 from road transport related combustion are also significant with respect to trends over the time series.

When considering the contribution of the LULUCF sector to 2020 emissions and sinks, 43 categories accounted for 95 percent of emissions and sinks, with the most significant category from LULUCF being net CO_2 emission from Forest Land Remaining Forest Land. When considering uncertainties and the contribution of the LULUCF sector,

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[33] See Chapter 4 Volume 1, "Methodological Choice and Identification of Key Categories" in IPCC (2006). See http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

additional categories such as CO_2 emissions from Grasslands Remaining Grasslands were also identified as a key category. In the trend analysis, 41 categories were identified as key, and when considering uncertainties, 7 additional categories were identified as key. The trend analysis includes additional categories such as non-CO_2 emissions from forest fires as key categories in the LULUCF sector.

Finally, in addition to conducting Approach 1 and 2 level and trend assessments as described above, a qualitative assessment of the source and sinks categories was conducted to capture any additional key categories that were not identified using the previously described quantitative approaches. For this inventory, no additional categories were identified using qualitative criteria recommend by IPCC, but EPA continues to review its qualitative assessment on an annual basis. Find more information regarding the overall key category analysis in Annex 1 to this report.

Table 1-4: Key Categories for the United States (1990 and 2020)

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2020 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
Energy										
CO_2 Emissions from Mobile Combustion: Road	CO_2	•	•	•	•	•	•	•	•	1,333.8
CO_2 Emissions from Stationary Combustion - Coal - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	788.2
CO_2 Emissions from Stationary Combustion - Gas - Electricity Generation	CO_2	•	•	•	•	•	•	•	•	634.3
CO_2 Emissions from Stationary Combustion - Gas - Industrial	CO_2	•	•	•	•	•	•	•	•	485.5
CO_2 Emissions from Stationary Combustion - Gas - Residential	CO_2	•	•	•	•	•		•		256.4
CO_2 Emissions from Stationary Combustion - Oil - Industrial	CO_2	•	•	•	•	•	•	•	•	237.8
CO_2 Emissions from Stationary Combustion - Gas - Commercial	CO_2	•	•	•	•	•	•	•		173.9
CO_2 Emissions from Mobile Combustion: Aviation	CO_2	•	•	•	•	•	•	•	•	121.3
CO_2 Emissions from Non-Energy Use of Fuels	CO_2	•	•	•	•	•	•	•	•	121.0

CRF Source/Sink Categories	Gas	Approach 1				Approach 2 (includes uncertainty)				2020 Emissions (MMT CO_2 Eq.)
		Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	
CO_2 Emissions from Stationary Combustion - Oil - Residential	CO_2	•	•	•	•		•			59.5
CO_2 Emissions from Mobile Combustion: Other[a]	CO_2	•	•	•	•					57.1
CO_2 Emissions from Stationary Combustion - Oil - Commercial	CO_2	•	•	•	•					51.6
CO_2 Emissions from Stationary Combustion - Coal - Industrial	CO_2	•	•	•	•	•	•	•	•	43.0
CO_2 Emissions from Natural Gas Systems	CO_2	•		•		•				35.4
CO_2 Emissions from Mobile Combustion: Railways	CO_2	•		•						31.0
CO_2 Emissions from Petroleum Systems	CO_2	•	•	•	•	•	•	•	•	30.2
CO_2 Emissions from Mobile Combustion: Marine	CO_2	•	•	•	•					23.7
CO_2 Emissions from Stationary Combustion - Oil - U.S. Territories	CO_2	•		•						16.9
CO_2 Emissions from Stationary Combustion - Oil - Electricity Generation	CO_2	•	•	•	•	•	•		•	16.2
CO_2 Emissions from Mobile Combustion: Military	CO_2		•		•					5.2
CO_2 Emissions from Coal Mining	CO_2						•			2.2
CO_2 Emissions from Stationary Combustion - Coal - Commercial	CO_2		•		•		•			1.4
CO_2 Emissions from Stationary Combustion - Coal - Residential	CO_2						•		•	-
CH_4 Emissions from Natural Gas Systems	CH_4	•	•	•	•	•	•	•	•	164.9
Fugitive Emissions from Coal Mining	CH_4	•	•	•	•	•	•	•	•	41.2

		Approach 1				Approach 2 (includes uncertainty)				2020
CRF Source/Sink Categories	Gas	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Level Without LULUCF	Trend Without LULUCF	Level With LULUCF	Trend With LULUCF	Emissions (MMT CO_2 Eq.)
CH_4 Emissions from Petroleum Systems	CH_4	•	•	•	•	•	•	•	•	40.2
CH_4 Emissions from Abandoned Oil and Gas Wells	CH_4					•		•		6.9
CH_4 Emissions from Stationary Combustion - Residential	CH_4					•	•	•	•	4.1
N_2O Emissions from Stationary Combustion - Coal - Electricity Generation	N_2O	•		•		•	•	•	•	15.2
N_2O Emissions from Mobile Combustion: Road	N_2O	•	•	•	•				•	9.8
N_2O Emissions from Stationary Combustion - Gas - Electricity Generation	N_2O						•			4.5
N_2O Emissions from Stationary Combustion - Industrial	N_2O					•				2.3
Industrial Processes and Product Use										
CO_2 Emissions from Cement Production	CO_2	•	•	•	•					40.7
CO_2 Emissions from Iron and Steel Production & Metallurgical Coke Production	CO_2	•	•	•	•	•	•	•	•	37.7
CO_2 Emissions from Petrochemical Production	CO_2	•	•	•	•					30.0
Emissions from Substitutes for Ozone Depleting Substances: Refrigeration and Air conditioning	HFCs, PFCs	•	•	•	•	•	•	•	•	137.7
Emissions from Substitutes for Ozone Depleting Substances: Aerosols	HFCs, PFCs	•	•	•	•	•	•	•	•	18.1

CRF Source/Sink Categories	Gas	Approach 1 Level Without LULUCF	Approach 1 Trend Without LULUCF	Approach 1 Level With LULUCF	Approach 1 Trend With LULUCF	Approach 2 (includes uncertainty) Level Without LULUCF	Approach 2 (includes uncertainty) Trend Without LULUCF	Approach 2 (includes uncertainty) Level With LULUCF	Approach 2 (includes uncertainty) Trend With LULUCF	2020 Emissions (MMT CO_2 Eq.)
Emissions from Substitutes for Ozone Depleting Substances: Foam Blowing Agents	HFCs, PFCs		•		•					15.5
SF_6 and CF_4 Emissions from Electrical Transmission and Distribution	SF_6, CF_4	•	•	•	•		•		•	3.8
HFC-23 Emissions from HCFC-22 Production	HFCs	•	•	•	•		•		•	2.1
PFC Emissions from Aluminum Production	PFCs	•	•	•	•					1.7
Agriculture										
CO_2 Emissions from Liming	CO_2						•		•	2.4
CH_4 Emissions from Enteric Fermentation: Cattle	CH_4	•	•	•	•	•	•	•		168.9
CH_4 Emissions from Manure Management: Cattle	CH_4	•	•	•	•	•	•		•	33.5
CH_4 Emissions from Manure Management: Other Livestock	CH_4	•		•	•					26.1
CH_4 Emissions from Rice Cultivation	CH_4	•		•		•		•		15.7
Direct N_2O Emissions from Agricultural Soil Management	N_2O	•		•		•		•		271.7
Indirect N_2O Emissions from Applied Nitrogen	N_2O	•		•		•		•		44.6
Waste										
CH_4 Emissions from Commercial Landfills	CH_4	•	•	•	•	•	•	•	•	94.2
CH_4 Emissions from Domestic Wastewater Treatment	CH_4					•				11.8
N_2O Emissions from Domestic Wastewater Treatment	N_2O	•		•		•		•	•	23.0
Land Use, Land-Use Change, and Forestry										

CRF Source/Sink Categories	Gas	Approach 1 Level Without LULUCF	Approach 1 Trend Without LULUCF	Approach 1 Level With LULUCF	Approach 1 Trend With LULUCF	Approach 2 (includes uncertainty) Level Without LULUCF	Approach 2 (includes uncertainty) Trend Without LULUCF	Approach 2 (includes uncertainty) Level With LULUCF	Approach 2 (includes uncertainty) Trend With LULUCF	2020 Emissions (MMT CO_2 Eq.)
Net CO_2 Emissions from Land Converted to Settlements	CO_2			•	•			•	•	77.9
Net CO_2 Emissions from Land Converted to Cropland	CO_2			•				•	•	54.4
Net CO_2 Emissions from Grassland Remaining Grassland	CO_2							•	•	4.5
Net CO_2 Emissions from Cropland Remaining Cropland	CO_2			•				•		(23.3)
Net CO_2 Emissions from Land Converted to Grassland	CO_2			•	•			•	•	(24.1)
Net CO_2 Emissions from Land Converted to Forest Land	CO_2			•				•		(99.5)
Net CO_2 Emissions from Settlements Remaining Settlements	CO_2			•	•			•	•	(126.1)
Net CO_2 Emissions from Forest Land Remaining Forest Land	CO_2			•	•			•	•	(668.1)
CH_4 Emissions from Flooded Lands Remaining Flooded Lands	CH_4			•						19.9
CH_4 Emissions from Forest Fires	CH_4				•				•	13.6
N_2O Emissions from Forest Fires	N_2O				•				•	11.7
Subtotal of Key Categories Without LULUCF[b]										**5,793.6**
Total Gross Emissions Without LULUCF										**5,981.4**
Percent of Total Without LULUCF										**97%**
Subtotal of Key Categories With LULUCF[c]										**5,013.7**
Total Net Emissions With LULUCF										**5,222.4**
Percent of Total With LULUCF										**96%**

[a] Other includes emissions from pipelines.

[b] Subtotal includes key categories from Level Approach 1 Without LULUCF, Level Approach 2 Without LULUCF, Trend Approach 1 Without LULUCF, and Trend Approach 2 Without LULUCF.

[c] Subtotal includes key categories from Level Approach 1 With LULUCF, Level Approach 2 With LULUCF, Trend Approach 1 With LULUCF, and Trend Approach 2 With LULUCF.

Note: Parentheses indicate negative values (or sequestration).

1.6 Quality Assurance and Quality Control (QA/QC)

As part of efforts to achieve its stated goals for inventory quality, transparency, and credibility, the United States has developed a quality assurance and quality control plan designed to check, document, and improve the quality of its inventory over time. QA/QC activities on the Inventory are undertaken within the framework of the U.S. *Quality Assurance/Quality Control and Uncertainty Management Plan* (QA/QC plan) *for the U.S. Greenhouse Gas Inventory: Procedures Manual for QA/QC and Uncertainty Analysis*.

Key attributes of the QA/QC plan are summarized in Figure 1-2. These attributes include:

- *Procedures and Forms:* detailed and specific systems that serve to standardize the process of documenting and archiving information, as well as to guide the implementation of QA/QC and the analysis of uncertainty
- *Implementation of Procedures:* application of QA/QC procedures throughout the whole Inventory development process from initial data collection, through preparation of the emission and removal estimates, to publication of the Inventory
- *Quality Assurance (QA):* expert and public reviews for both the inventory estimates and the Inventory report (which is the primary vehicle for disseminating the results of the inventory development process). The expert technical review conducted by the UNFCCC supplements these QA processes, consistent with the QA good practice and the *2006 IPCC Guidelines* (IPCC 2006)
- *Quality Control (QC)*: application of *General (Tier 1) and Category-specific (Tier 2)* quality controls and checks, as recommended by *2006 IPCC Guidelines* (IPCC 2006), along with consideration of secondary data and category-specific checks (additional Tier 2 QC) in parallel and coordination with the uncertainty assessment; the development of protocols and templates, which provides for more structured communication and integration with the suppliers of secondary information
- *General (Tier 1) and Category-specific (Tier 2) Checks:* quality controls and checks, as recommended by *IPCC Good Practice Guidance* and *2006 IPCC Guidelines* (IPCC 2006)
- *Record Keeping:* provisions to track which procedures have been followed, the results of the QA/QC, uncertainty analysis, and feedback mechanisms for corrective action based on the results of the investigations which provide for continual data quality improvement and guided research efforts.
- *Multi-Year Implementation*: a schedule for coordinating the application of QA/QC procedures across multiple years, especially for category-specific QC, prioritizing key categories
- *Interaction and Coordination:* promoting communication within the EPA, across Federal agencies and departments, state government programs, and research institutions and consulting firms involved in supplying data or preparing estimates for the Inventory. The QA/QC Management Plan itself is intended to be revised and reflect new information that becomes available as the program develops, methods are improved, or additional supporting documents become necessary.

Figure 1-2: U.S. QA/QC Plan Summary

	Data Gathering	Data Documentation	Calculating Emissions	Cross-Cutting Coordination
Inventory Analyst	• Obtain data in electronic format (if possible) • Review spreadsheet construction ○ Avoid hardwiring ○ Use data validation ○ Protect cells • Develop automatic checkers for: ○ Outliers, negative values, or missing data ○ Variable types match values ○ Time series consistency • Maintain tracking tab for status of gathering efforts	• Contact reports for non-electronic communications • Provide cell references for primary data elements • Obtain copies of all data sources • List and location of any working/external spreadsheets • Document assumptions • Complete QA/QC checklists • CRF and summary tab links	• Clearly label parameters, units, and conversion factors • Review spreadsheet integrity ○ Equations ○ Units ○ Inputs and outputs • Develop automated checkers for: ○ Input ranges ○ Calculations ○ Emission aggregation ○ Trend and IEF checks	• Common starting versions for each inventory year • Utilize unalterable summary and CRF tab for each source spreadsheet for linking to a master summary spreadsheet • Follow strict version control procedures • Document QA/QC procedures
QA/QC Analyst	• Check input data for transcription errors • Inspect automatic checkers • Identify spreadsheet modifications that could provide additional QA/QC checks	• Check citations in spreadsheet and text for accuracy and style • Check reference docket for new citations • Review documentation for any data / methodology changes • Complete QA/QC checklists • CRF and summary tab links	• Reproduce calculations • Review time series consistency • Review changes in data/consistency with IPCC methodology	

Box 1-3: Use of IPCC Reference Approach to support Verification of Emissions from Fossil Fuel Combustion

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their "bottom-up" sectoral methodology for purposes of verification. This estimation method uses alternative methodologies and different data sources than those contained in that section of the Energy chapter. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys (see Annex 4 of this report). The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required.

In addition, based on the national QA/QC plan for the Inventory, some sector, subsector and category-specific QA/QC and verification checks have been developed. These checks follow the procedures outlined in the national QA/QC plan, tailoring the procedures to the specific documentation and data files associated with individual sources. For each greenhouse gas emissions source or sink category included in this Inventory, a minimum of general or Tier 1 QC analysis has been undertaken. Where QC activities for a particular category go beyond the minimum Tier 1 level, and include category-specific checks (Tier 2) or include verification, further explanation is provided within the respective source or sink category text. Similarly, responses or updates based on comments from the expert, public and the international technical expert reviews (e.g., UNFCCC) are also addressed within the respective source or sink category sections in each sectoral chapter and Annex 8.

The quality control activities described in the U.S. QA/QC plan occur throughout the inventory process; QA/QC is not separate from, but is an integral part of, preparing the Inventory. Quality control—in the form of both good practices (such as documentation procedures) and checks on whether good practices and procedures are being followed—is applied at every stage of inventory development and document preparation. In addition, quality assurance occurs during the Expert Review and the Public Review, in addition to the UNFCCC expert technical review. While all phases significantly contribute to improving inventory quality, the public review phase is also essential for promoting the openness of the inventory development process and the transparency of the inventory data and methods.

The QA/QC plan guides the process of ensuring inventory quality by describing data and methodology checks, developing processes governing peer review and public comments, and developing guidance on conducting an analysis of the uncertainty surrounding the emission and removal estimates. The QA/QC procedures also include feedback loops and provide for corrective actions that are designed to improve the inventory estimates over time.

1.7 Uncertainty Analysis of Emission Estimates

Emissions calculated for the U.S. Inventory reflect best estimates for greenhouse gas source and sink categories in the United States and are continuously revised and improved as new information becomes available. Uncertainty assessment is an essential element of a complete and transparent emissions inventory because it helps inform and prioritize Inventory improvements. For the U.S. Inventory, uncertainty analyses are conducted for each source and sink category as well as for the uncertainties associated with the overall emission (current and base year) and trends estimates. These analyses reflect the quantitative uncertainty in the emission (and removal) estimates associated with uncertainties in their input parameters (e.g., activity data and EFs) and serve to evaluate the relative contribution of individual input parameter uncertainties to the overall Inventory, its trends, and each source and sink category.

The overall uncertainty estimate for total U.S. greenhouse gas emissions was developed using the IPCC Approach 2 uncertainty estimation methodology, which employs a Monte Carlo Stochastic Simulation technique. The IPCC provides good practice guidance on two approaches—Approach 1 and Approach 2—to estimating uncertainty for both individual and combined source categories. Approach 2 quantifies uncertainties based on a distribution of emissions (or removals), built-up from repeated calculations of emission estimation models and the underlying input parameters, randomly selected according to their known distributions. Approach 2 methodology is applied to each individual source and sink category wherever data and resources are permitted and is also used to quantify the uncertainty in the overall Inventory and its Trends. Source and sink chapters in this report provide additional details on the uncertainty analysis conducted for each source and sink category. See Annex 7 of this report for further details on the U.S. process for estimating uncertainty associated with the overall emission (base and current year) and trends estimates. Consistent with IPCC (IPCC 2006), the United States has ongoing efforts to continue to improve the overall Inventory uncertainty estimates presented in this report.

The United States has also implemented many improvements over the last several years to reduce uncertainties across the source and sink categories and improve Inventory estimates. These improvements largely result from new data sources that provide more accurate data and/or increased data coverage, as well as methodological improvements. Following IPCC good practice, additional efforts to reduce Inventory uncertainties can occur through efforts to incorporate excluded emission and sink categories (see Annex 5), improve emission estimation methods, and collect more detailed, measured, and representative data. Individual source chapters and Annex 7 both describe current ongoing and planned Inventory and uncertainty analysis improvements. Consistent with IPCC (2006), the United States has ongoing efforts to continue to improve the category-specific uncertainty estimates presented in this report, largely prioritized by considering improvements categories identified as significant by the Key Category Analysis.

Estimates of quantitative uncertainty for the total U.S. greenhouse gas emissions in 1990 (base year) and 2020 are shown below in Table 1-5 and Table 1-6, respectively. The overall uncertainty surrounding the Total Net Emissions is estimated to be -5 to +6 percent in 1990 and -5 to +6 percent in 2020. When the LULUCF sector is excluded from the analysis the uncertainty is estimated to be -2 to +5 percent in 1990 and -2 to +5 percent in 2020.

Table 1-5: Estimated Overall Inventory Quantitative Uncertainty for 1990 (MMT CO_2 Eq. and Percent)

Gas	1990 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)		(MMT CO_2 Eq.)	
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	5,122.5	5,017.3	5,357.6	-2%	5%	5,186.5	88.0
CH_4[d]	780.8	720.1	871.5	-8%	12%	794.9	38.8
N_2O[d]	450.5	365.6	574.9	-19%	28%	457.8	54.1
PFC, HFC, SF_6, and NF_3[d]	99.7	90.2	112.5	-9%	13%	100.4	5.6
Total Gross Emissions	**6,453.5**	**6,330.2**	**6,761.5**	**-2%**	**5%**	**6,539.5**	**110.6**
LULUCF Emissions[e]	31.4	29.3	33.8	-7%	8%	31.5	1.1
LULUCF Carbon Stock Change Flux[f]	(892.0)	(1,183.9)	(709.3)	33%	-20%	(944.1)	119.3
LULUCF Sector Net Total[g]	**(860.6)**	**(1,152.7)**	**(677.7)**	**34%**	**-21%**	**(912.6)**	**119.3**
Net Emissions (Sources and Sinks)	**5,592.8**	**5,306.8**	**5,953.6**	**-5%**	**6%**	**5,626.9**	**163.9**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

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[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 1990.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[f] LULUCF Carbon Stock Change is the net C stock change from the following categories: Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, *Wetlands Remaining Wetlands*, Land Converted to Wetlands, Settlements Remaining Settlements, and Land Converted to Settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

[g] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 1-6: Estimated Overall Inventory Quantitative Uncertainty for 2020 (MMT CO_2 Eq. and Percent)

Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]				Mean[b]	Standard Deviation[b]
		(MMT CO_2 Eq.)		(%)		(MMT CO_2 Eq.)	
		Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound		
CO_2	4,715.7	4,610.6	4,908.0	-2%	4%	4,759.8	76.4
CH_4[d]	650.4	595.9	723.6	-8%	11%	659.7	32.6
N_2O[d]	426.1	342.4	551.1	-20%	29%	436.1	53.3
PFC, HFC, SF_6, and NF_3[d]	189.2	182.6	213.7	-3%	13%	198.2	7.9
Total Gross Emissions	**5,981.4**	**5,863.8**	**6,253.0**	**-2%**	**5%**	**6,053.7**	**98.2**
LULUCF Emissions[e]	53.2	44.4	62.9	-17%	18%	53.5	4.9
LULUCF Carbon Stock Change Flux[f]	(812.2)	(1,075.7)	(647.8)	32%	-20%	(860.2)	109.4
LULUCF Sector Net Total[g]	**(758.9)**	**(1,023.2)**	**(594.5)**	**35%**	**-22%**	**(806.7)**	**109.6**
Net Emissions (Sources and Sinks)	**5,222.4**	**4,956.9**	**5,540.9**	**-5%**	**6%**	**5,247.0**	**148.1**

[a] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.

[b] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.

[c] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.

[d] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for CH_4, N_2O and high GWP gases used in the Inventory emission calculations for 2020.

[e] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[f] LULUCF Carbon Stock Change is the net C stock change from the following categories: Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, Land Converted to Grassland, *Wetlands Remaining Wetlands*, Land Converted to Wetlands, Settlements Remaining Settlements, and Land Converted to Settlements. Since the resulting flux is negative the signs of the resulting lower and upper bounds are reversed.

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[g] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

In addition to the estimates of uncertainty associated with the current and base year emission estimates, Table 1-7 presents the estimates of inventory trend uncertainty. The *2006 IPCC Guidelines* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2020) Inventory estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this Inventory as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty associated with this emission trend is referred to as trend uncertainty and is reported as between -14 and 1 percent at the 95 percent confidence level between 1990 and 2020. This indicates a range of approximately -7 percent below and 8 percent above the emission trend estimate of -7 percent. See Annex 7 for trend uncertainty estimates for individual source and sink categories by gas.

Table 1-7: Quantitative Assessment of Trend Uncertainty (MMT CO_2 Eq. and Percent)

Gas/Source	Base Year Emissions[a]	2020 Emissions	Emissions Trend	Trend Range[b]	
	(MMT CO_2 Eq.)		(%)	(%)	
				Lower Bound	Upper Bound
CO_2	5,122.5	4,715.7	-8%	-12%	-4%
CH_4	780.8	650.4	-17%	-28%	-5%
N_2O	450.5	426.1	-5%	-31%	32%
HFCs, PFCs, SF_6, and NF_3	99.7	189.2	90%	73%	125%
Total Gross Emissions[c]	**6,453.5**	**5,981.4**	**-7%**	**-12%**	**-3%**
LULUCF Emissions[d]	31.4	53.2	70%	39%	103%
LULUCF Carbon Stock Change Flux[e]	(892.0)	(812.2)	-9%	-37%	30%
LULUCF Sector Net Total[f]	**(860.6)**	**(758.9)**	**-12%**	**-40%**	**28%**
Net Emissions (Sources and Sinks)[c]	**5,592.8**	**5,222.4**	**-7%**	**-14%**	**1%**

[a] Base Year is 1990 for all sources.

[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5th percentile value and the upper bound corresponding to 97.5th percentile value.

[c] Totals exclude emissions for which uncertainty was not quantified.

[d] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Land Converted to Flooded Land, and Flooded Land Remaining Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements*, and Land Converted to Settlements.

[f] The LULUCF Sector Net Total is the net sum of all CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration. Total emissions (excluding emissions for which uncertainty was not quantified) are presented without LULUCF. Net emissions are presented with LULUCF.

1.8 Completeness

This report, along with its accompanying CRF tables, serves as a thorough assessment of the anthropogenic sources and sinks of greenhouse gas emissions for the United States for the time series 1990 through 2020. This report is intended to be comprehensive and includes the vast majority of emissions and removals identified as anthropogenic, consistent with IPCC and UNFCCC guidelines. In general, sources or sink categories not accounted for in this Inventory are excluded because they are not occurring in the United States, or because data are unavailable to develop an estimate and/or the categories were determined to be insignificant[34] in terms of overall national emissions per UNFCCC reporting guidelines.

The United States is continually working to improve upon the understanding of such sources and sinks currently not included and seeking to find the data required to estimate related emissions and removals, focusing on categories that are anticipated to be significant. As such improvements are implemented, new emission and removal estimates are quantified and included in the Inventory, improving completeness of national estimates. For a list of sources and sink categories not included and more information on significance of these categories, see Annex 5 and the respective category sections in each sectoral chapter of this report.

1.9 Organization of Report

In accordance with the revision of the UNFCCC reporting guidelines agreed to at the nineteenth Conference of the Parties (UNFCCC 2014), this *Inventory of U.S. Greenhouse Gas Emissions and Sinks* is grouped into five sector-specific chapters consistent with the UN Common Reporting Framework, listed below in Table 1-8. In addition, chapters on Trends in Greenhouse Gas Emissions, Other information, and Recalculations and Improvements to be considered as part of the U.S. Inventory submission are included.

Table 1-8: IPCC Sector Descriptions

Chapter (IPCC Sector)	Activities Included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities including fuel combustion and fugitive fuel emissions, and non-energy use of fossil fuels.
Industrial Processes and Product Use	Emissions resulting from industrial processes and product use of greenhouse gases.
Agriculture	Emissions from agricultural activities except fuel combustion, which is addressed under Energy.
Land Use, Land-Use Change, and Forestry	Emissions and removals of CO_2, and emissions of CH_4, and N_2O from land use, land-use change and forestry.
Waste	Emissions from waste management activities.

Within each chapter, emissions are identified by the anthropogenic activity that is the source or sink of the greenhouse gas emissions being estimated (e.g., coal mining). Overall, the following organizational structure is consistently applied throughout this report:

Chapter/IPCC Sector: Overview of emissions and trends for each IPCC defined sector.

CRF Source or Sink Category: Description of category pathway and emission/removal trends based on IPCC methodologies, consistent with UNFCCC reporting guidelines.

Methodology: Description of analytical methods (e.g., from *2006 IPCC Guidelines,* or country-specific methods) employed to produce emission estimates and identification of data references, primarily for activity data and emission factors.

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[34] See paragraph 32 of Decision 24/CP.19, the UNFCCC reporting guidelines on annual inventories for Parties included in Annex 1 to the Convention. Paragraph notes that "…An emission should only be considered insignificant if the likely level of emissions is below 0.05 per cent of the national total GHG emissions, and does not exceed 500 kt CO_2 Eq. The total national aggregate of estimated emissions for all gases and categories considered insignificant shall remain below 0.1 percent of the national total GHG emissions."

Uncertainty and Time-Series Consistency: A discussion and quantification of the uncertainty in emission estimates and a discussion of time-series consistency.

QA/QC and Verification: A discussion on steps taken to QA/QC and verify the emission estimates, consistent with the U.S. QA/QC plan, and any key QC findings.

Recalculations Discussion: A discussion of any data or methodological changes that necessitate a recalculation of previous years' emission estimates, and the impact of the recalculation on the emission estimates, if applicable.

Planned Improvements: A discussion on any category-specific planned improvements, if applicable.

Special attention is given to CO_2 from fossil fuel combustion relative to other sources because of its share of emissions and its dominant influence on emission trends. For example, each energy consuming end-use sector (i.e., residential, commercial, industrial, and transportation), as well as the electricity generation sector, is described individually. Additional information for certain source categories and other topics is also provided in several Annexes listed in Table 1-9.

Table 1-9: List of Annexes

ANNEX 1	Key Category Analysis
ANNEX 2	Methodology and Data for Estimating CO_2 Emissions from Fossil Fuel Combustion
2.1.	Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion
2.2.	Methodology for Estimating the Carbon Content of Fossil Fuels
2.3.	Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels
ANNEX 3	Methodological Descriptions for Additional Source or Sink Categories
3.1.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Stationary Combustion
3.2.	Methodology for Estimating Emissions of CH_4, N_2O, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions
3.3.	Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption
3.4.	Methodology for Estimating CH_4 Emissions from Coal Mining
3.5.	Methodology for Estimating CH_4 and CO_2 Emissions from Petroleum Systems
3.6.	Methodology for Estimating CH_4 Emissions from Natural Gas Systems
3.7.	Methodology for Estimating CO_2 and N_2O Emissions from Incineration of Waste
3.8.	Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military
3.9.	Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances
3.10.	Methodology for Estimating CH_4 Emissions from Enteric Fermentation
3.11.	Methodology for Estimating CH_4 and N_2O Emissions from Manure Management
3.12.	Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Lands (Cropland and Grassland)
3.13.	Methodology for Estimating Net Carbon Stock Changes in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*
3.14.	Methodology for Estimating CH_4 Emissions from Landfills
ANNEX 4	IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion
ANNEX 5	Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included
ANNEX 6	Additional Information
6.1.	Global Warming Potential Values
6.2.	Ozone Depleting Substance Emissions
6.3.	Complete List of Source Categories
6.4.	Constants, Units, and Conversions
6.5.	Chemical Formulas
6.6.	Greenhouse Gas Precursors: Cross-Walk of NEI categories to the Inventory
ANNEX 7	Uncertainty
7.1.	Overview
7.2.	Methodology and Results
7.3.	Reducing Uncertainty
7.4.	Planned Improvements
7.5.	Additional Information on Uncertainty Analyses by Source
ANNEX 8	QA/QC Procedures

2. Trends in Greenhouse Gas Emissions

2.1 Trends in U.S. Greenhouse Gas Emissions and Sinks

In 2020, total gross U.S. greenhouse gas emissions were 5,981.4 million metric tons carbon dioxide equivalent (MMT CO_2 Eq).[1] Total U.S. emissions have decreased by 7.3 percent from 1990 to 2020, down from a high of 15.7 percent above 1990 levels in 2007. Emissions decreased from 2019 to 2020 by 9.0 percent (590.4 MMT CO_2 Eq.). Net emissions (i.e., including sinks) were 5,222.4 MMT CO_2 Eq. in 2020. Overall, net emissions decreased 10.6 percent from 2019 to 2020 and decreased 21.4 percent from 2005 levels, as shown in Table 2-1. The sharp decline in emissions from 2019 to 2020 is largely due to the impacts of the coronavirus (COVID-19) pandemic on travel and economic activity; however, the decline also reflects the combined impacts of long-term trends in many factors, including population, economic growth, energy markets, technological changes including energy efficiency, and the carbon intensity of energy fuel choices. Between 2019 and 2020, the decrease in total greenhouse gas emissions was driven largely by a 10.5 percent decrease in CO_2 emissions from fossil fuel combustion, including a 13.3 percent decrease in transportation sector emissions from less travel due to the COVID-19 pandemic and a 10.4 percent decrease in the electric power sector. The decrease in electric power sector emissions was due to a decrease in electricity demand of 2.5 percent since 2019 and also reflects the continued shift from coal to less carbon intensive natural gas and renewables.

Figure 2-1 and Figure 2-2 illustrate the overall trend in total U.S. emissions and sinks by gas, annual changes, and relative changes since 1990.

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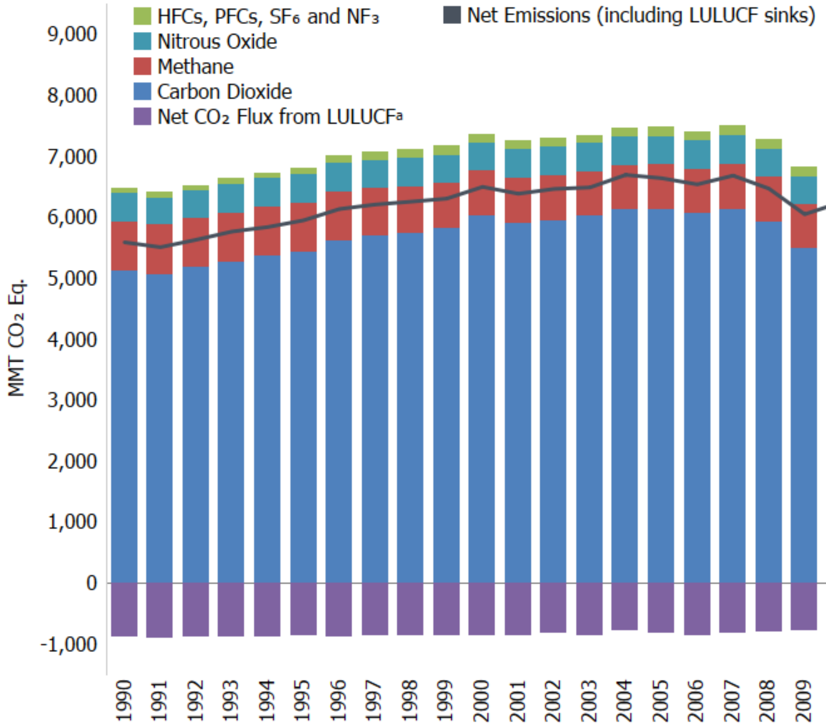
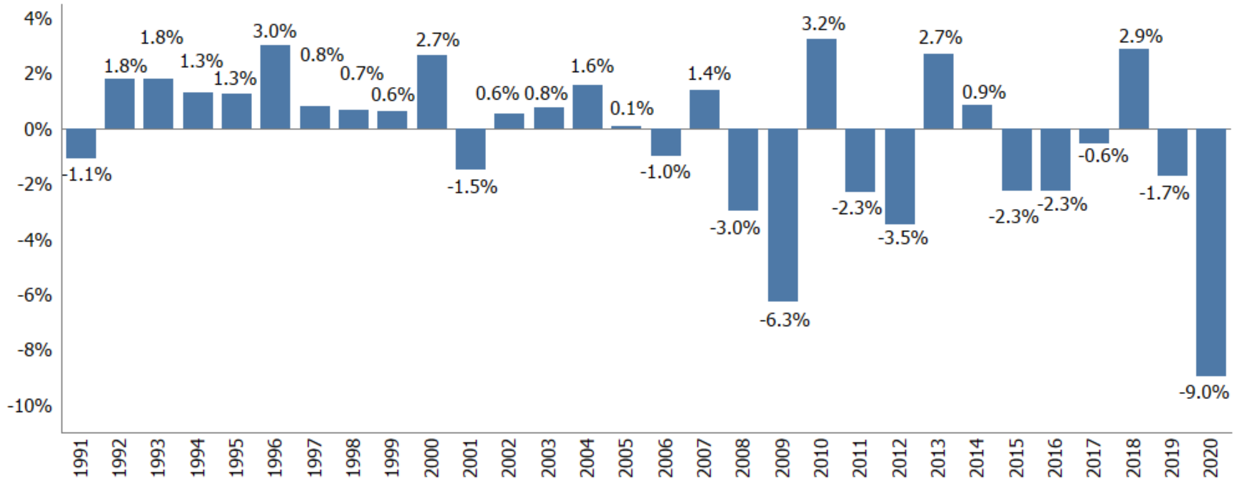
[1] The gross emissions total presented in this report for the United States excludes emissions and sinks from removals from Land Use, Land-Use Change, and Forestry (LULUCF). The net emissions total presented in this report for the United States includes emissions and sinks from removals from LULUCF.

Figure 2-1: U.S. Greenhouse Gas Emissions and Sinks by Gas



[a] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Figure 2-2: Annual Percent Change in Gross U.S. Greenhouse Gas Emissions Relative to the Previous Year



Overall from 1990 to 2020, total emissions of CO_2 decreased by 406.8 MMT CO_2 Eq. (7.9 percent), as total emissions of methane (CH_4) decreased by 130.4 MMT CO_2 Eq. (16.7 percent), and total emissions of nitrous oxide (N_2O) decreased by 24.4 MMT CO_2 Eq. (5.4 percent). During the same period, emissions of fluorinated gases including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) rose by 89.5 MMT CO_2 Eq. (89.8 percent). Despite being emitted in smaller quantities relative to the other principal greenhouse gases, emissions of HFCs, PFCs, SF_6, and NF_3 are significant because many of them have extremely high global warming potentials (GWPs), and, in the cases of PFCs, SF_6, and NF_3, long atmospheric lifetimes. Conversely, U.S. greenhouse gas emissions were partly offset by carbon (C) sequestration in managed forests, trees in urban areas, agricultural soils, landfilled yard trimmings, and coastal wetlands. These were estimated to offset 13.6 percent (812.2 MMT CO_2 Eq.) of total emissions in 2020.

Table 2-1 provides information on trends in emissions and sinks from all U.S. anthropogenic sources in weighted units of MMT CO_2 Eq., while unweighted gas emissions and sinks in kilotons (kt) are provided in Table 2-2.

Table 2-1: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**5,122.5**	**6,137.6**	**5,251.8**	**5,211.0**	**5,376.7**	**5,259.1**	**4,715.7**
Fossil Fuel Combustion	4,731.2	5,752.0	4,909.6	4,853.3	4,989.3	4,852.3	4,342.7
Transportation	*1,468.9*	*1,858.6*	*1,757.6*	*1,780.0*	*1,812.8*	*1,813.8*	*1,572.0*
Electric Power Sector	*1,820.0*	*2,400.1*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.1*	*1,439.0*
Industrial	*853.7*	*851.5*	*792.7*	*790.4*	*814.1*	*816.1*	*766.3*
Residential	*338.6*	*358.9*	*292.8*	*293.4*	*338.2*	*341.4*	*315.8*
Commercial	*228.3*	*227.1*	*231.5*	*232.0*	*245.8*	*250.7*	*226.8*
U.S. Territories	*21.7*	*55.9*	*26.0*	*25.5*	*25.5*	*24.3*	*22.7*
Non-Energy Use of Fuels	112.2	128.9	99.5	112.6	128.9	126.8	121.0
Cement Production	33.5	46.2	39.4	40.3	39.0	40.9	40.7
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	43.6	40.6	42.6	43.1	37.7
Natural Gas Systems	31.9	24.9	29.8	31.1	32.4	38.7	35.4
Petroleum Systems	9.6	12.0	21.9	25.0	37.3	46.7	30.2
Petrochemical Production	21.6	27.4	28.1	28.9	29.3	30.7	30.0
Incineration of Waste	12.9	13.3	14.4	13.2	13.3	12.9	13.1
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7
Lime Production	11.7	14.6	12.6	12.9	13.1	12.1	11.3
Other Process Uses of Carbonates	6.2	7.5	10.8	9.9	7.4	9.8	9.8
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	5.3	5.2	6.0	6.0	6.0
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3
Carbon Dioxide Consumption	1.5	1.4	4.6	4.6	4.1	4.9	5.0
Liming	4.7	4.3	3.1	3.1	2.2	2.4	2.4
Coal Mining	4.6	4.2	2.8	3.1	3.1	3.0	2.2
Glass Production	2.3	2.4	2.1	2.0	2.0	1.9	1.9
Aluminum Production	6.8	4.1	1.3	1.2	1.5	1.9	1.7
Soda Ash Production	1.4	1.7	1.7	1.8	1.7	1.8	1.5
Ferroalloy Production	2.2	1.4	1.8	2.0	2.1	1.6	1.4
Titanium Dioxide Production	1.2	1.8	1.7	1.7	1.5	1.5	1.3
Zinc Production	0.6	1.0	0.8	0.9	1.0	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	0.9	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Magnesium Production and Processing	0.1	+	+	+	+	+	+
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219.4*	*230.7*	*316.9*	*312.7*	*319.8*	*317.2*	*291.6*
International Bunker Fuels[b]	*103.6*	*113.3*	*116.7*	*120.2*	*122.2*	*116.1*	*69.6*
CH_4[c]	**780.8**	**697.5**	**657.6**	**663.8**	**671.1**	**668.8**	**650.4**
Enteric Fermentation	163.5	168.0	171.3	174.9	175.7	176.1	175.2
Natural Gas Systems	195.5	177.5	165.2	166.6	171.8	172.1	164.9
Landfills	176.6	131.5	107.9	109.2	111.7	113.6	109.3

Manure Management	34.8	49.0	57.1	57.5	59.4	58.7	59.6
Coal Mining	96.5	64.1	53.8	54.8	52.7	47.4	41.2
Petroleum Systems	47.8	41.4	40.4	40.5	38.6	40.4	40.2
Wastewater Treatment	20.3	20.1	18.7	18.5	18.3	18.1	18.3
Rice Cultivation	16.0	18.0	15.8	14.9	15.6	15.1	15.7
Stationary Combustion	8.6	7.8	7.9	7.7	8.6	8.8	7.9
Abandoned Oil and Gas Wells	6.5	6.8	6.9	6.9	6.9	7.0	6.9
Abandoned Underground Coal Mines	7.2	6.6	6.7	6.4	6.2	5.9	5.8
Composting	0.4	1.9	2.3	2.5	2.3	2.3	2.3
Mobile Combustion	6.5	4.0	2.6	2.6	2.5	2.5	2.2
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Petrochemical Production	0.2	0.1	0.2	0.3	0.3	0.3	0.3
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O[c]	**450.5**	**453.3**	**449.2**	**444.6**	**457.7**	**456.8**	**426.1**
Agricultural Soil Management	316.0	313.8	330.8	328.3	338.9	345.3	316.2
Wastewater Treatment	16.6	20.3	22.8	23.2	23.5	23.4	23.5
Stationary Combustion	25.1	34.4	30.0	28.4	28.2	24.9	23.2
Manure Management	13.9	16.3	18.4	19.0	19.3	19.5	19.7
Mobile Combustion	44.6	41.4	21.1	20.1	19.2	20.0	17.4
Nitric Acid Production	12.1	11.3	10.1	9.3	9.6	10.0	9.3
Adipic Acid Production	15.2	7.1	7.1	7.5	10.5	5.3	8.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Composting	0.3	1.7	2.0	2.2	2.0	2.0	2.0
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.7	1.5	1.4	1.4	1.2
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Electronics Industry	+	0.1	0.2	0.3	0.3	0.2	0.3
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*	*0.6*
HFCs	**46.5**	**127.4**	**168.3**	**171.1**	**171.0**	**175.9**	**178.8**
Substitution of Ozone Depleting Substances[d]	0.2	107.2	165.1	165.5	167.3	171.8	176.2
HCFC-22 Production	46.1	20.0	2.8	5.2	3.3	3.7	2.1
Electronics Industry	0.2	0.2	0.3	0.4	0.4	0.4	0.4
Magnesium Production and Processing	NO	NO	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**4.4**	**4.2**	**4.8**	**4.6**	**4.4**
Electronics Industry	2.8	3.3	3.0	3.0	3.1	2.8	2.7
Aluminum Production	21.5	3.4	1.4	1.1	1.6	1.8	1.7
Substitution of Ozone Depleting Substances[d]	NO	+	+	+	0.1	0.1	0.1
Electrical Transmission and Distribution	NO	+	+	+	NO	+	+

SF_6	**28.8**	**11.8**	**6.0**	**5.9**	**5.7**	**5.9**	**5.4**
Electrical Transmission and Distribution	23.2	8.3	4.1	4.2	3.8	4.2	3.8
Magnesium Production and Processing	5.2	2.7	1.1	1.0	1.0	0.9	0.9
Electronics Industry	0.5	0.7	0.8	0.7	0.8	0.8	0.7
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Emissions[c]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change[e]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[f]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

[e] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, *Cropland Remaining Cropland*, Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland*, *Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements*, and Land Converted to Settlements. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[f] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total(gross) emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Table 2-2: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**5,122,496**	**6,137,603**	**5,251,758**	**5,210,958**	**5,376,657**	**5,259,144**	**4,715,691**
Fossil Fuel Combustion	4,731,178	5,752,043	4,909,609	4,853,299	4,989,308	4,852,330	4,342,659
Transportation	*1,468,944*	*1,858,552*	*1,757,638*	*1,779,977*	*1,812,761*	*1,813,755*	*1,572,034*
Electric Power Sector	*1,819,951*	*2,400,057*	*1,808,872*	*1,732,033*	*1,752,936*	*1,606,106*	*1,438,990*
Industrial	*853,707*	*851,522*	*792,743*	*790,402*	*814,096*	*816,107*	*766,317*
Residential	*338,578*	*358,898*	*292,773*	*293,410*	*338,218*	*341,400*	*315,846*
Commercial	*228,298*	*227,130*	*231,547*	*231,999*	*245,838*	*250,703*	*226,815*
U.S. Territories	*21,700*	*55,883*	*26,036*	*25,478*	*25,459*	*24,259*	*22,657*
Non-Energy Use of Fuels	112,175	128,920	99,505	112,616	128,871	126,776	120,987
Cement Production	33,484	46,194	39,439	40,324	38,971	40,896	40,688
Iron and Steel Production & Metallurgical Coke Production	104,737	70,076	43,621	40,566	42,627	43,090	37,731
Natural Gas Systems	31,894	24,945	29,780	31,145	32,407	38,740	35,353
Petroleum Systems	9,600	11,994	21,922	25,027	37,306	46,686	30,156
Petrochemical Production	21,611	27,383	28,110	28,890	29,314	30,702	30,011

Incineration of Waste	12,937	13,283	14,356	13,161	13,339	12,948	13,133
Ammonia Production	13,047	9,177	10,245	11,112	12,163	12,272	12,717
Lime Production	11,700	14,552	12,630	12,882	13,106	12,112	11,299
Other Process Uses of Carbonates	6,233	7,459	10,813	9,869	7,351	9,848	9,794
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	5,330	5,182	6,030	6,044	5,983
Urea Fertilization	2,417	3,504	4,679	4,897	5,019	5,140	5,275
Carbon Dioxide Consumption	1,472	1,375	4,640	4,580	4,130	4,870	4,970
Liming	4,667	4,349	3,081	3,080	2,248	2,413	2,382
Coal Mining	4,606	4,170	2,848	3,067	3,067	2,951	2,169
Glass Production	2,291	2,432	2,119	2,011	1,989	1,938	1,857
Aluminum Production	6,831	4,142	1,334	1,205	1,451	1,880	1,748
Soda Ash Production	1,431	1,655	1,723	1,753	1,714	1,792	1,461
Ferroalloy Production	2,152	1,392	1,796	1,975	2,063	1,598	1,377
Titanium Dioxide Production	1,195	1,755	1,662	1,688	1,541	1,474	1,340
Zinc Production	632	1,030	838	900	999	1,026	1,008
Phosphoric Acid Production	1,529	1,342	998	1,025	937	909	938
Lead Production	516	553	500	513	513	527	495
Carbide Production and Consumption	243	213	170	181	184	175	154
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Magnesium Production and Processing	129	3	3	3	2	1	1
Wood Biomass, Ethanol, and Biodiesel Consumption[a]	*219,413*	*230,700*	*316,853*	*312,717*	*319,805*	*317,231*	*291,613*
International Bunker Fuels[b]	*103,634*	*113,328*	*116,682*	*120,192*	*122,179*	*116,132*	*69,638*
CH_4[c]	**31,233**	**27,898**	**26,304**	**26,550**	**26,844**	**26,753**	**26,017**
Enteric Fermentation	6,539	6,722	6,853	6,998	7,028	7,046	7,007
Natural Gas Systems	7,821	7,100	6,609	6,662	6,871	6,885	6,596
Landfills	7,063	5,262	4,318	4,368	4,467	4,545	4,373
Manure Management	1,394	1,960	2,285	2,300	2,375	2,348	2,383
Coal Mining	3,860	2,565	2,154	2,191	2,109	1,895	1,648
Petroleum Systems	1,912	1,655	1,616	1,621	1,544	1,615	1,609
Wastewater Treatment	812	806	748	740	732	723	730
Rice Cultivation	640	720	631	596	623	602	630
Stationary Combustion	344	313	315	307	344	351	317
Abandoned Oil and Gas Wells	261	273	275	276	277	279	276
Abandoned Underground Coal Mines	288	264	268	257	247	237	231
Composting	15	75	91	98	90	91	91
Mobile Combustion	259	161	105	102	99	99	88
Field Burning of Agricultural Residues	15	17	17	17	17	17	17
Petrochemical Production	9	3	10	10	12	13	13
Anaerobic Digestion at Biogas Facilities	1	2	7	6	6	6	6
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	1	1	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*4*	*4*	*3*

N_2O[c]	**1,512**	**1,521**	**1,507**	**1,492**	**1,536**	**1,533**	**1,430**
Agricultural Soil Management	1,060	1,053	1,110	1,102	1,137	1,159	1,061
Wastewater Treatment	56	68	76	78	79	79	79
Stationary Combustion	84	115	101	95	95	84	78
Manure Management	47	55	62	64	65	65	66
Mobile Combustion	150	139	71	68	64	67	58
Nitric Acid Production	41	38	34	31	32	34	31
Adipic Acid Production	51	24	24	25	35	18	28
N_2O from Product Uses	14	14	14	14	14	14	14
Composting	1	6	7	7	7	7	7
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	6	5	5	5	4
Incineration of Waste	2	1	1	1	1	1	1
Electronics Industry	+	+	1	1	1	1	1
Field Burning of Agricultural Residues	1	1	1	1	1	1	1
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*3*	*4*	*4*	*3*	*2*
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[d]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	NO	NO	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances[d]	NO	+	+	+	+	+	+
Electrical Transmission and Distribution	NO	+	+	+	NO	+	+
SF_6	**1**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
NF_3	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
CO	**130,085**	**66,912**	**35,882**	**34,752**	**33,743**	**32,734**	**31,725**
NO_x	**21,712**	**17,191**	**8,686**	**8,296**	**7,869**	**7,374**	**6,883**
SO_2	**20,935**	**13,196**	**2,906**	**2,303**	**2,211**	**1,943**	**1,780**
NMVOCs	**20,923**	**13,309**	**9,855**	**9,483**	**9,310**	**9,136**	**8,963**

+ Does not exceed 0.5 kt.

M (Mixture of multiple gases)

NO (Not Occurring)

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

[c] LULUCF emissions of LULUCF CH_4 and N_2O are reported separately from gross emissions totals. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Small amounts of PFC emissions also result from this source.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Emissions of all gases can be summed from each source category into a set of five sectors defined by the Intergovernmental Panel on Climate Change (IPCC). Figure 2-3 and Table 2-3 illustrate that over the thirty-one-year period of 1990 to 2020, total emissions from the Energy and Waste sectors decreased by 486.5 MMT CO_2 Eq. (9.1 percent) and 58.6 MMT CO_2 Eq. (27.4 percent), respectively. Emissions from Industrial Processes and Product Use and Agriculture grew by 30.2 MMT CO_2 Eq. (8.7 percent) and 42.8 MMT CO_2 Eq. (7.8 percent), respectively. Over the same period, total C sequestration in the Land Use, Land-Use Change, and Forestry (LULUCF) sector decreased by 79.8 MMT CO_2 (9.0 percent decrease in total C sequestration), and emissions from the LULUCF sector increased by 21.8 MMT CO_2 Eq. (69.6 percent).

Figure 2-3: U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector

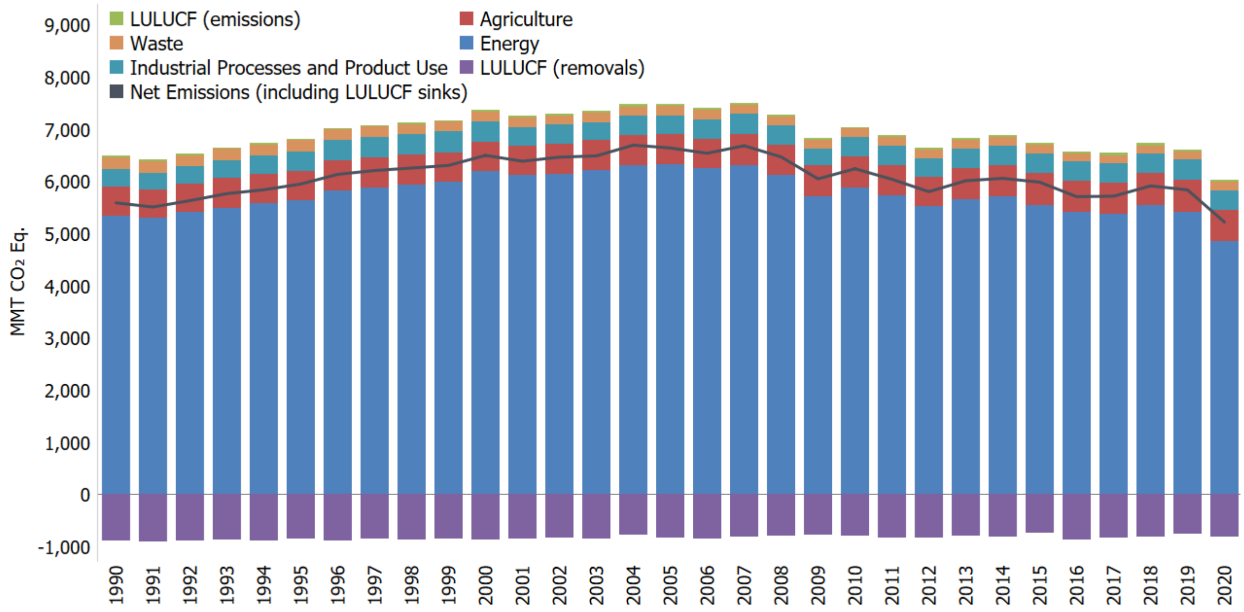


Table 2-3: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks by IPCC Sector/Category (MMT CO_2 Eq.)

IPCC Sector/Category	1990	2005	2016	2017	2018	2019	2020
Energy	**5,341.1**	**6,319.8**	**5,413.1**	**5,372.7**	**5,539.4**	**5,409.8**	**4,854.7**
Fossil Fuel Combustion	4,731.2	5,752.0	4,909.6	4,853.3	4,989.3	4,852.3	4,342.7
Natural Gas Systems	227.4	202.5	195.0	197.7	204.2	210.9	200.3
Non-Energy Use of Fuels	112.2	128.9	99.5	112.6	128.9	126.8	121.0
Petroleum Systems	57.4	53.4	62.3	65.6	75.9	87.1	70.4
Coal Mining	101.1	68.3	56.7	57.9	55.8	50.3	43.4
Stationary Combustion[a]	33.7	42.2	37.9	36.1	36.8	33.7	31.2
Mobile Combustion[a]	51.1	45.4	23.7	22.7	21.6	22.4	19.6
Incineration of Waste	13.4	13.7	14.8	13.6	13.8	13.4	13.5
Abandoned Oil and Gas Wells	6.5	6.8	6.9	6.9	6.9	7.0	6.9
Abandoned Underground Coal Mines	7.2	6.6	6.7	6.4	6.2	5.9	5.8
Industrial Processes and Product Use	**346.2**	**365.9**	**369.0**	**369.4**	**373.4**	**379.5**	**376.4**
Substitution of Ozone Depleting Substances	0.2	107.2	165.1	165.5	167.3	171.8	176.3
Cement Production	33.5	46.2	39.4	40.3	39.0	40.9	40.7

Iron and Steel Production & Metallurgical Coke Production	104.8	70.1	43.6	40.6	42.6	43.1	37.7
Petrochemical Production	21.8	27.5	28.4	29.1	29.6	31.0	30.3
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7
Lime Production	11.7	14.6	12.6	12.9	13.1	12.1	11.3
Other Process Uses of Carbonates	6.2	7.5	10.8	9.9	7.4	9.8	9.8
Nitric Acid Production	12.1	11.3	10.1	9.3	9.6	10.0	9.3
Adipic Acid Production	15.2	7.1	7.1	7.5	10.5	5.3	8.3
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	5.3	5.2	6.0	6.0	6.0
Carbon Dioxide Consumption	1.5	1.4	4.6	4.6	4.1	4.9	5.0
Electronics Industry	3.6	4.8	5.0	4.9	5.1	4.7	4.7
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Electrical Transmission and Distribution	23.2	8.4	4.1	4.2	3.8	4.2	3.8
Aluminum Production	28.3	7.6	2.7	2.3	3.1	3.6	3.4
HCFC-22 Production	46.1	20.0	2.8	5.2	3.3	3.7	2.1
Glass Production	2.3	2.4	2.1	2.0	2.0	1.9	1.9
Soda Ash Production	1.4	1.7	1.7	1.8	1.7	1.8	1.5
Ferroalloy Production	2.2	1.4	1.8	2.0	2.1	1.6	1.4
Titanium Dioxide Production	1.2	1.8	1.7	1.7	1.5	1.5	1.3
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.7	1.5	1.4	1.4	1.2
Zinc Production	0.6	1.0	0.8	0.9	1.0	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	0.9	0.9	0.9
Magnesium Production and Processing	5.3	2.7	1.2	1.1	1.1	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Agriculture	**551.9**	**573.6**	**601.9**	**603.2**	**616.7**	**622.9**	**594.7**
Agricultural Soil Management	316.0	313.8	330.8	328.3	338.9	345.3	316.2
Enteric Fermentation	163.5	168.0	171.3	174.9	175.7	176.1	175.2
Manure Management	48.8	65.3	75.5	76.5	78.7	78.2	79.2
Rice Cultivation	16.0	18.0	15.8	14.9	15.6	15.1	15.7
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3
Liming	4.7	4.3	3.1	3.1	2.2	2.4	2.4
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Waste	**214.2**	**175.6**	**153.9**	**155.7**	**157.9**	**159.6**	**155.6**
Landfills	176.6	131.5	107.9	109.2	111.7	113.6	109.3
Wastewater Treatment	36.9	40.5	41.5	41.7	41.8	41.5	41.8
Composting	0.7	3.5	4.3	4.6	4.3	4.3	4.3
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2
Total Gross Emissions[b] (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[c]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Forest land	(868.3)	(773.0)	(816.7)	(769.6)	(764.2)	(731.4)	(741.7)
Cropland	28.6	23.0	31.4	32.0	37.4	39.4	31.0
Grassland	4.0	(27.6)	(14.0)	(12.7)	(12.1)	(8.4)	(19.0)
Wetlands	21.9	18.5	16.5	16.6	16.5	16.5	16.5
Settlements	(46.8)	(30.7)	(43.8)	(47.4)	(46.9)	(46.6)	(45.8)
Net Emission (Sources and Sinks)[d]	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes CH_4 and N_2O emissions from fuel combustion.

[b] Total emissions without LULUCF.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals. LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands,* Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils. Refer to Table 2-8 for a breakout of emissions and removals for LULUCF by gas and source category.

[d] Net emissions with LULUCF.

Notes: Total (gross) emissions presented without LULUCF. Net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Energy

Energy-related activities, primarily fossil fuel combustion, accounted for the vast majority of U.S. CO_2 emissions for the period of 1990 through 2020. Fossil fuel combustion is the largest source of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 2-4). Due to their relative importance, fossil fuel combustion-related CO_2 emissions are considered in detail in the Energy chapter (see Energy chapter).

In 2020, 78.8 percent of the energy used in the United States (on a Btu basis) was produced through the combustion of fossil fuels. The remaining 21.2 percent came from other energy sources such as hydropower, biomass, nuclear, wind, and solar energy. A discussion of specific trends related to CO_2 as well as other greenhouse gas emissions from energy use is presented here with more detail in the Energy chapter. Energy-related activities are also responsible for CH_4 and N_2O emissions (41.4 percent and 9.6 percent of total U.S. emissions of each gas, respectively). Table 2-4 presents greenhouse gas emissions from the Energy chapter, by source and gas.

Figure 2-4: Trends in Energy Sector Greenhouse Gas Sources

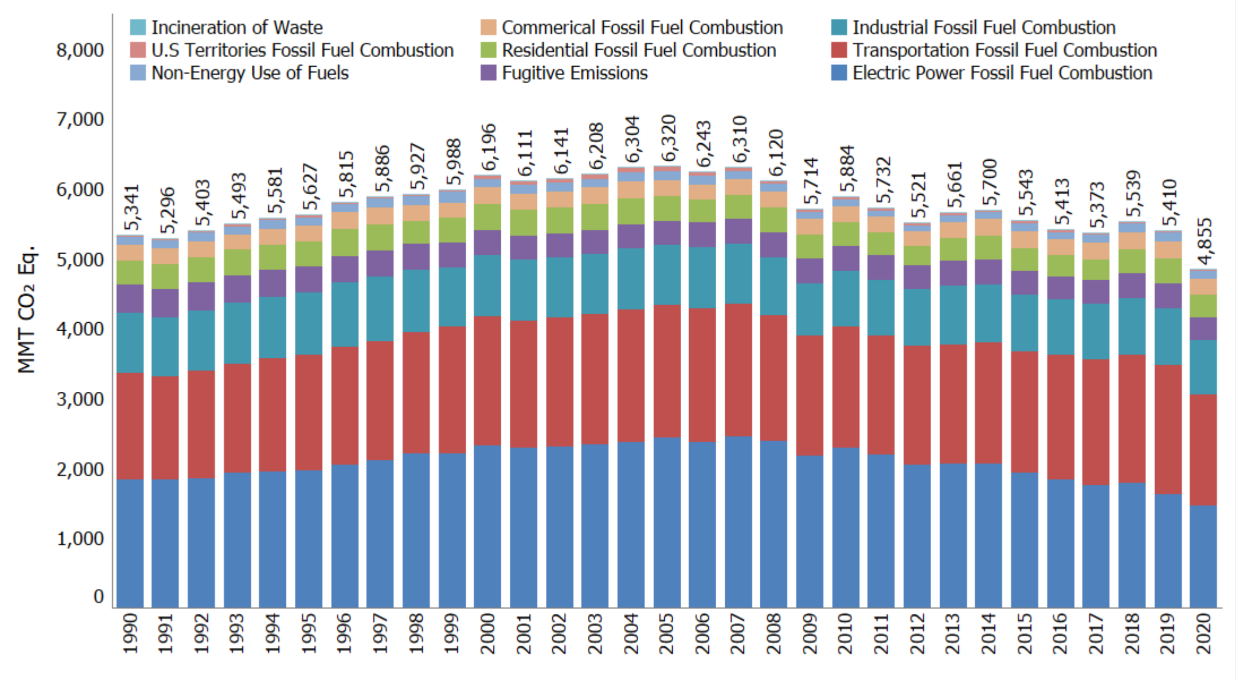


Table 2-4: Emissions from Energy (MMT CO_2 Eq.)[2]

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**4,902.4**	**5,935.4**	**5,078.0**	**5,038.3**	**5,204.3**	**5,080.4**	**4,544.5**

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[2] The full time series data is available in Common Reporting Format (CRF) Tables included in the U.S. UNFCCC submission and in CSV format available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Fossil Fuel Combustion	4,731.2	5,752.0	4,909.6	4,853.3	4,989.3	4,852.3	4,342.7
Transportation	*1,468.9*	*1,858.6*	*1,757.6*	*1,780.0*	*1,812.8*	*1,813.8*	*1,572.0*
Electricity Generation	*1,820.0*	*2,400.1*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.1*	*1,439.0*
Industrial	*853.7*	*851.5*	*792.7*	*790.4*	*814.1*	*816.1*	*766.3*
Residential	*338.6*	*358.9*	*292.8*	*293.4*	*338.2*	*341.4*	*315.8*
Commercial	*228.3*	*227.1*	*231.5*	*232.0*	*245.8*	*250.7*	*226.8*
U.S. Territories	*21.7*	*55.9*	*26.0*	*25.5*	*25.5*	*24.3*	*22.7*
Non-Energy Use of Fuels	112.2	128.9	99.5	112.6	128.9	126.8	121.0
Natural Gas Systems	31.9	24.9	29.8	31.1	32.4	38.7	35.4
Petroleum Systems	9.6	12.0	21.9	25.0	37.3	46.7	30.2
Incineration of Waste	12.9	13.3	14.4	13.2	13.3	12.9	13.1
Coal Mining	4.6	4.2	2.8	3.1	3.1	3.0	2.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood [a]	*215.2*	*206.9*	*216.0*	*211.9*	*220.0*	*217.6*	*202.1*
Biofuels-Ethanol [a]	*4.2*	*22.9*	*81.2*	*82.1*	*81.9*	*82.6*	*71.8*
International Bunker Fuels[b]	*103.6*	*113.3*	*116.7*	*120.2*	*122.2*	*116.1*	*69.6*
Biofuels-Biodiesel [a]	*0.0*	*0.9*	*19.6*	*18.7*	*17.9*	*17.1*	*17.7*
CH_4	**368.6**	**308.3**	**283.5**	**285.4**	**287.3**	**284.0**	**269.1**
Natural Gas Systems	195.5	177.5	165.2	166.6	171.8	172.1	164.9
Coal Mining	96.5	64.1	53.8	54.8	52.7	47.4	41.2
Petroleum Systems	47.8	41.4	40.4	40.5	38.6	40.4	40.2
Stationary Combustion	8.6	7.8	7.9	7.7	8.6	8.8	7.9
Abandoned Oil and Gas Wells	6.5	6.8	6.9	6.9	6.9	7.0	6.9
Abandoned Underground Coal Mines	7.2	6.6	6.7	6.4	6.2	5.9	5.8
Mobile Combustion	6.5	4.0	2.6	2.6	2.5	2.5	2.2
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**70.1**	**76.1**	**51.5**	**49.0**	**47.9**	**45.3**	**41.1**
Stationary Combustion	25.1	34.4	30.0	28.4	28.2	24.9	23.2
Mobile Combustion	44.6	41.4	21.1	20.1	19.2	20.0	17.4
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*	*0.6*
Total	**5,341.1**	**6,319.8**	**5,413.1**	**5,372.7**	**5,539.4**	**5,409.8**	**4,854.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals.

Note: Totals may not sum due to independent rounding.

CO_2 Emissions from Fossil Fuel Combustion

As the largest contributor to U.S. greenhouse gas emissions, CO_2 from fossil fuel combustion has accounted for approximately 75.3 percent of gross emissions across the time series. Within the United States, fossil fuel combustion accounted for 92.1 percent of CO_2 emissions in 2020. Emissions from this source category decreased by 8.2 percent (388.5 MMT CO_2 Eq.) from 1990 to 2020 and were responsible for most of the decrease in national emissions during this period. Similarly, CO_2 emissions from fossil fuel combustion decreased by 1,409.4 MMT CO_2 Eq. from 2005 and by 1,003.0 MMT CO_2 Eq. from 2010, representing decreases of 24.5 percent between 2005 and 2020 and 18.8 percent between 2010 and 2020. From 2019 to 2020, these emissions decreased by 10.5 percent (509.7 MMT CO_2 Eq.). Historically, changes in emissions from fossil fuel combustion have been the main factor influencing U.S. emission trends.

Changes in CO_2 emissions from fossil fuel combustion since 1990 are affected by many long-term and short-term factors, including population and economic growth, energy price fluctuations and market trends, technological changes, carbon intensity of energy fuel choices, and seasonal temperatures. CO_2 emissions from coal combustion gradually increased between 1990 and 2007, then began to decrease at a faster rate from 2008 to 2020. CO_2 emissions from natural gas combustion remained relatively constant, with a slight increase between 1990 and 2009, then began to consistently increase between 2010 and 2019. The replacement of coal combustion with natural gas combustion was largely driven by new discoveries of natural gas fields and advancements in drilling technologies, which led to more competitive natural gas prices. On an annual basis, the overall consumption and mix of fossil fuels in the United States fluctuates primarily in response to changes in general economic conditions, overall energy prices, the relative price of different fuels, weather, and the availability of non-fossil alternatives. For example, coal consumption for electric power is influenced by a number of factors, including the relative price of coal and alternative sources, the ability to switch fuels, and longer-term trends in coal markets. Likewise, warmer winters lead to a decrease in heating degree days and result in a decreased demand for heating fuel and electricity for heat in the residential and commercial sectors, which leads to a decrease in emissions from reduced fuel consumption. The decrease in 2020 emissions was due primarily to the COVID-19 pandemic reducing overall demand for fossil fuels across all sectors, but it also reflects a continued shift from coal to natural gas and renewables in the electric power sector.

Fossil fuel combustion CO_2 emissions also depend on the type of fuel consumed or energy used and its carbon intensity. Producing a unit of heat or electricity using natural gas instead of coal, for example, reduces CO_2 emissions because of the lower C content of natural gas (see Table A-22 in Annex 2.1 for more detail on the C Content Coefficient of different fossil fuels).

Recent trends in CO_2 emissions from fossil fuel combustion have been strongly influenced by trends in the electric power sector, which from 1990 to 2017 accounted for the largest share of emissions from this source (see Figure 2-12). Electric power sector emissions are driven by the total amount of electricity generated to meet electricity demand and the carbon intensity of the energy mix used to produce the electricity. From 1990 to 2005, power sector CO_2 emissions increased 31.9 percent with a 34.3 percent increase in generation (see Figure 2-7). From 2005 to 2020, power sector CO_2 emissions dropped 40.0 percent while generation remained relatively flat (a 1.4 percent decrease). The types of fuel consumed to produce electricity have shifted over time, impacting emission trends. Electricity generation from lower carbon intensity renewable energy sources increased by 132.3 percent from 2005 to 2020 and natural gas generation increased by 122.2 percent while coal generation decreased by 61.5 percent over the same time period (see Table 3-12 for more detail on electricity generation by source). The decrease in coal-powered electricity generation and increase in natural gas and renewable energy electricity generation have contributed to the 40.0 percent decrease in overall CO_2 emissions from electric power generation from 2005 to 2020 (see Figure 2-7). Between 2019 and 2020, emissions from the electric power sector decreased 10.4 percent due to a decrease in electric power generation of 2.9 percent and a decrease in the carbon intensity of the electric power energy mix reflecting the continued shift in the share of electric power generation from coal to natural gas and renewable energy.

Petroleum use is another major driver of CO_2 emissions from fossil fuel combustion, particularly in the transportation sector, which has represented the largest source of CO_2 emissions from fossil fuel combustion since 2018. Emissions from petroleum consumption for transportation (including bunker fuels) have decreased by 11.9 percent since 2016; this trend can be primarily attributed to a 11.0 percent decrease in vehicle miles traveled (VMT) from 2019 to 2020, due largely to the impacts of the coronavirus pandemic which limited travel in 2020. Fuel economy of light-duty vehicles is another important factor. The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period and has slowed the rate of increase of CO_2 emissions.

Overall, across all sectors, there was a 10.5 percent decrease in total CO_2 emissions from fossil fuel combustion from 2019 to 2020 and a 11.5 percent reduction since 2016. Trends in carbon dioxide emissions from fossil fuel combustion, separated by end-use sector, are presented in Table 2-5 and Figure 2-5 based on the underlying U.S. energy consumer data collected by the U.S. Energy Information Administration (EIA). Figure 2-6 further describes trends in direct and indirect CO_2 emissions from fossil fuel combustion, separated by end-use sector. Estimates of CO_2 emissions from fossil fuel combustion are calculated from these EIA "end-use sectors" based on total fuel consumption and appropriate fuel properties described below. (Any additional analysis and refinement of the EIA data is further explained in the Energy chapter of this report.)

- *Transportation.* EIA's fuel consumption data for the transportation sector consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.
- *Industry.* EIA statistics for the industrial sector include fossil fuel consumption that occurs in the fields of manufacturing, agriculture, mining, and construction. EIA's fuel consumption data for the industrial sector consist of all facilities and equipment used for producing, processing, or assembling goods. (EIA includes generators that produce electricity and/or useful thermal output primarily to support on-site industrial activities in this sector.)
- *Electric Power.* EIA's fuel consumption data for the electric power sector are comprised of electricity-only and combined-heat-and-power (CHP) plants within the North American Industry Classification System (NAICS) 22 category whose primary business is to sell electricity, or electricity and heat, to the public. (Non-utility power producers are included in this sector as long as they meet the electric power sector definition.)
- *Residential.* EIA's fuel consumption data for the residential sector consist of living quarters for private households.
- *Commercial.* EIA's fuel consumption data for the commercial sector consist of service-providing facilities and equipment from private and public organizations and businesses. (EIA includes generators that produce electricity and/or useful thermal output primarily to support the activities at commercial establishments in this sector.)

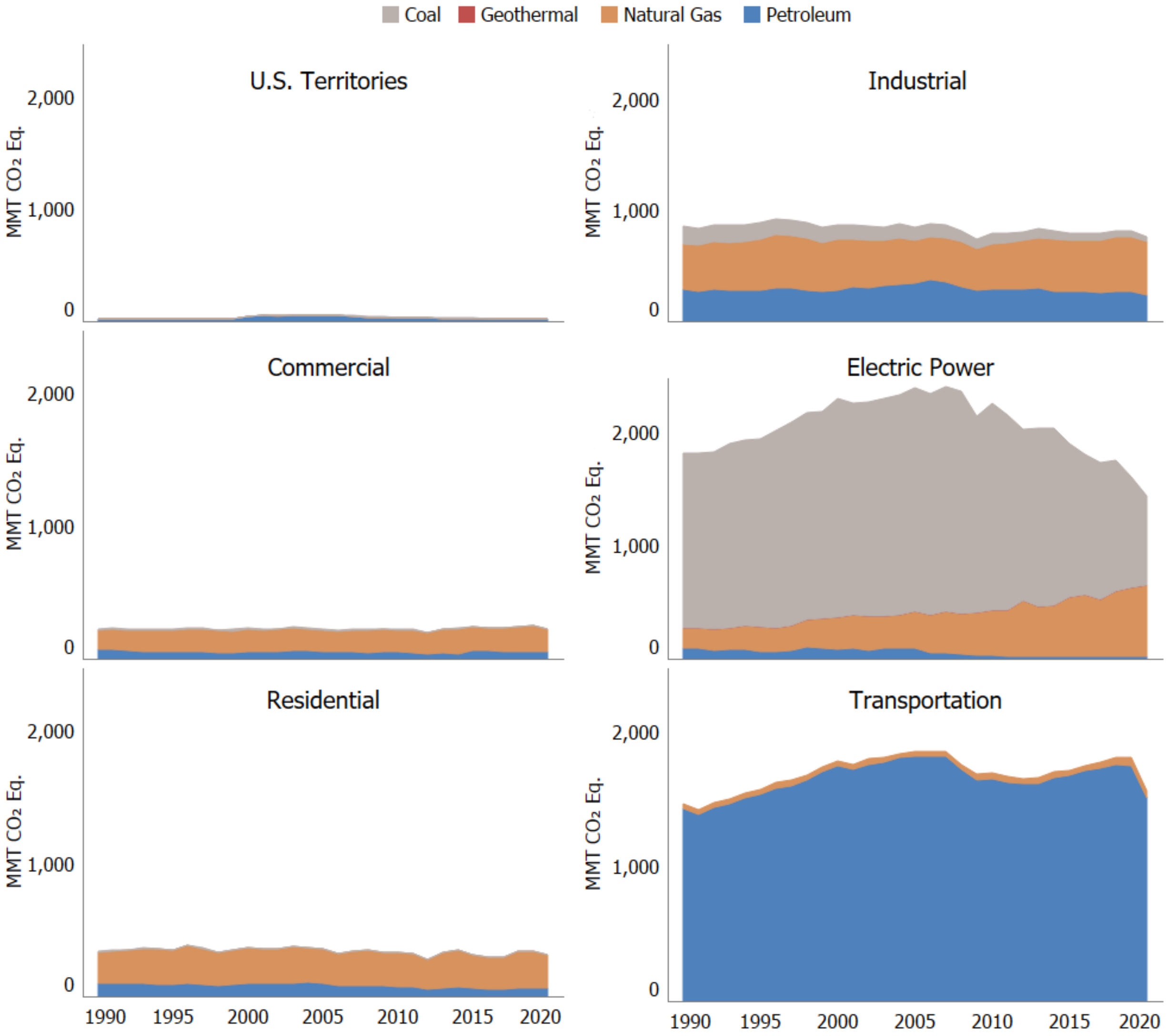
Table 2-5: CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation	**1,472.0**	**1,863.3**	**1,761.8**	**1,784.3**	**1,817.4**	**1,818.5**	**1,576.7**
Combustion	1,468.9	1,858.6	1,757.6	1,780.0	1,812.8	1,813.8	1,572.0
Electricity	3.0	4.7	4.2	4.3	4.7	4.7	4.7
Industrial	**1,540.1**	**1,587.8**	**1,310.3**	**1,294.8**	**1,315.3**	**1,281.4**	**1,175.8**
Combustion	853.7	851.5	792.7	790.4	814.1	816.1	766.3
Electricity	686.4	736.3	517.6	504.4	501.2	465.3	409.5
Residential	**931.3**	**1,214.9**	**946.2**	**910.5**	**980.4**	**925.0**	**860.6**
Combustion	338.6	358.9	292.8	293.4	338.2	341.4	315.8
Electricity	592.7	856.0	653.5	617.1	642.2	583.6	544.8
Commercial	**766.0**	**1,030.1**	**865.2**	**838.2**	**850.7**	**803.2**	**706.8**
Combustion	228.3	227.1	231.5	232.0	245.8	250.7	226.8
Electricity	537.7	803.0	633.6	606.2	604.9	552.5	480.0
U.S. Territories[a]	**21.7**	**55.9**	**26.0**	**25.5**	**25.5**	**24.3**	**22.7**
Total	**4,731.2**	**5,752.0**	**4,909.6**	**4,853.3**	**4,989.3**	**4,852.3**	**4,342.7**
Electric Power	**1,820.0**	**2,400.1**	**1,808.9**	**1,732.0**	**1,752.9**	**1,606.1**	**1,439.0**

[a] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands) is included in this report.

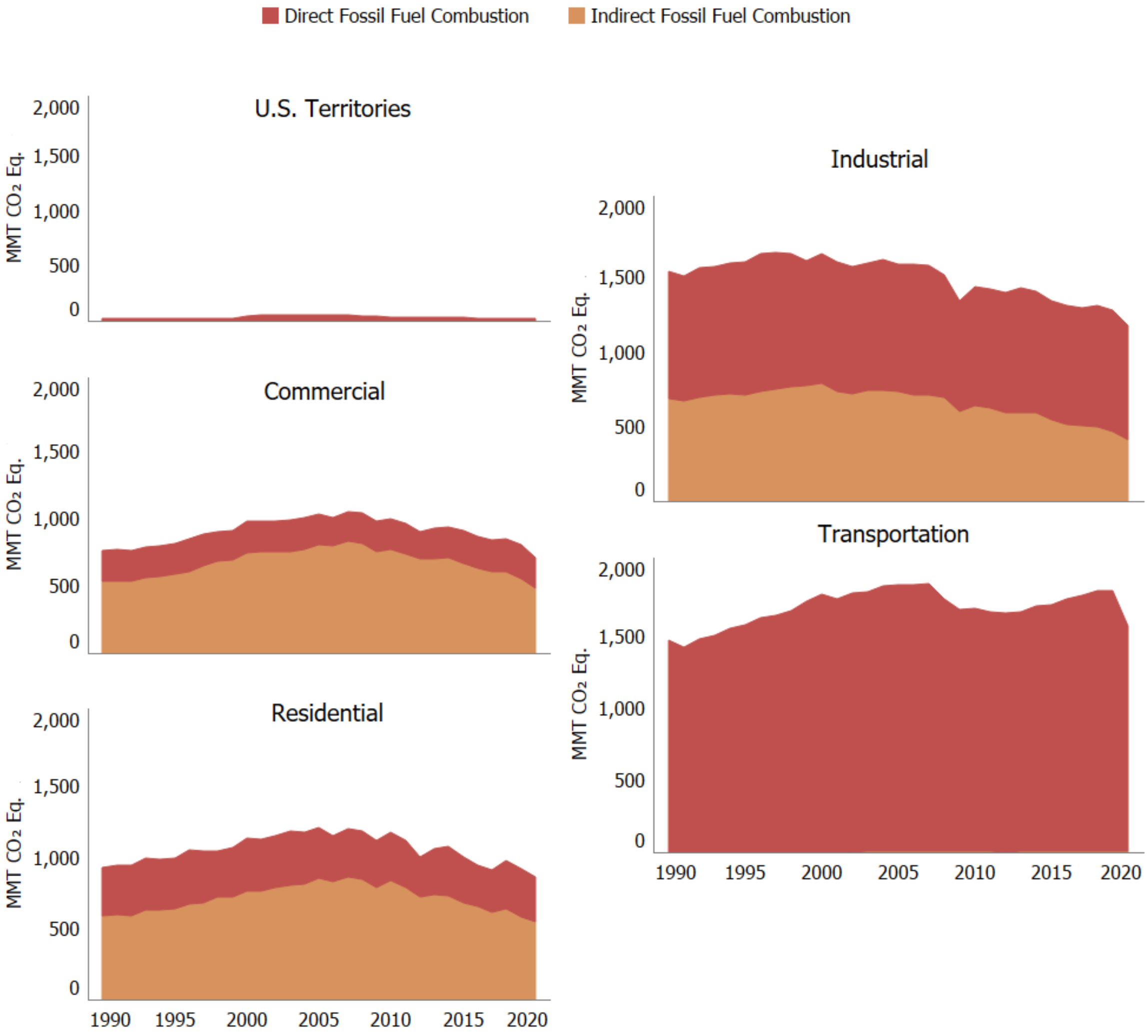
Notes: Combustion-related emissions from electric power are allocated based on aggregate national electricity use by each end-use sector. Totals may not sum due to independent rounding.

Figure 2-5: Trends in CO_2 Emissions from Fossil Fuel Combustion by End-Use Sector and Fuel Type



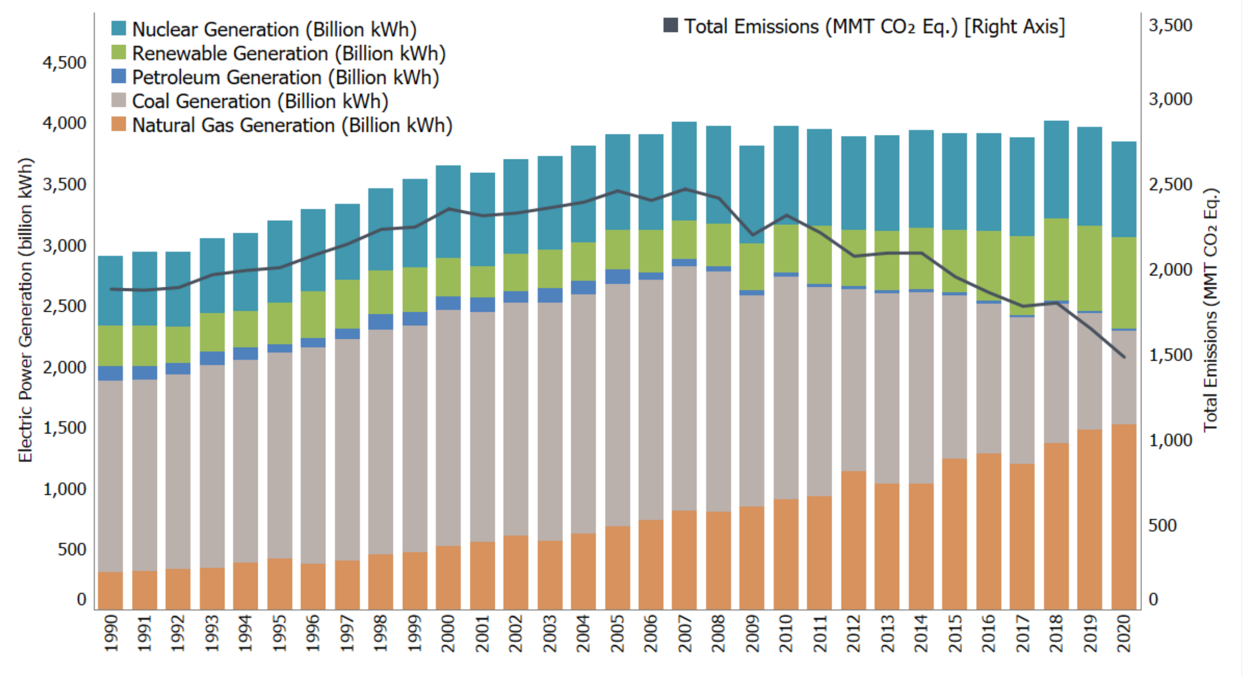
Note on Figure 2-5: Fossil Fuel Combustion for electric power also includes emissions of less than 0.5 MMT CO_2 Eq. from geothermal-based generation.

Figure 2-6: Trends in End-Use Sector Emissions of CO_2 from Fossil Fuel Combustion



Electric power was the second largest emitter of CO_2 in 2020 (surpassed by transportation); electric power generators used 31.2 percent of U.S. energy from fossil fuels and emitted 33.1 percent of the CO_2 from fossil fuel combustion in 2020. Changes in electricity demand and the carbon intensity of fuels used for electric power generation have a significant impact on CO_2 emissions. Carbon dioxide emissions from fossil fuel combustion from the electric power sector have decreased by 20.9 percent since 1990, and the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu input, has significantly decreased by 19.2 percent during that same timeframe. This decoupling of electric power generation and the resulting CO_2 emissions is shown below in Figure 2-7.

Figure 2-7: Electric Power Generation (Billion kWh) and Emissions (MMT CO_2 Eq.)



Electric power CO_2 emissions can also be allocated to the end-use sectors that use electricity, as presented in Table 2-5. With electricity CO_2 emissions allocated to end-use sectors, the transportation end-use sector represents the largest source of fossil fuel combustion emissions accounting for 1,576.7 MMT CO_2 Eq. in 2020 or 36.3 percent of total CO_2 emissions from fossil fuel combustion. The industrial end-use sector accounted for 27.1 percent of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. The residential and commercial end-use sectors accounted for 19.8 and 16.3 percent, respectively, of CO_2 emissions from fossil fuel combustion when including allocated electricity emissions. Both of these end-use sectors were heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances contributing 63.3 and 67.9 percent of emissions from the residential and commercial end-use sectors, respectively.

Other Significant Trends in Energy

Other significant trends in emissions from energy source categories (Figure 2-5 and Figure 2-6) over the thirty-one-year period from 1990 through 2020 included the following:

- Methane emissions from natural gas systems and petroleum systems (combined here) decreased 38.2 MMT CO_2 Eq. (15.7 percent decrease from 1990 to 2020) or from 243.3 MMT CO_2 Eq. in 1990 to 205.1 MMT CO_2 Eq. in 2020. Natural gas systems CH_4 emissions decreased by 30.6 MMT CO_2 Eq. (15.7 percent) since 1990, largely due to a decrease in emissions from distribution, transmission and storage, processing, and exploration. The decrease in distribution is largely due to decreased emissions from pipelines and distribution station leaks, and the decrease in transmission and storage emissions is largely due to reduced compressor station emissions (including emissions from compressors and leaks). At the same time, emissions from the natural gas production segment increased. Petroleum systems CH_4 emissions decreased by 7.6 MMT CO_2 Eq. (or 15.8 percent) since 1990. This decrease is due primarily to decreases in emissions from offshore platforms, tanks, and pneumatic controllers. Carbon dioxide emissions from natural gas and petroleum systems increased by 24.0 MMT CO_2 Eq. (57.9 percent) from 1990 to 2020. This increase is due primarily to increases in the production segment, where flaring emissions from associated gas flaring, tanks, and miscellaneous production flaring have increased over time.

- Methane emissions from coal mining decreased by 55.3 MMT CO_2 Eq. (57.3 percent) from 1990 through 2020, primarily due to a decrease in the number of active mines and annual coal production over the time period.
- Nitrous oxide emissions from mobile combustion decreased by 27.2 MMT CO_2 Eq. (61.0 percent) from 1990 through 2020, primarily as a result of national vehicle criteria pollutant emissions standards and emission control technologies for on-road vehicles.
- Carbon dioxide emissions from non-energy uses of fossil fuels increased by 8.8 MMT CO_2 Eq. (7.9 percent) from 1990 through 2020. Emissions from non-energy uses of fossil fuels were 121.0 MMT CO_2 Eq. in 2020, which constituted 2.6 percent of total national CO_2 emissions, approximately the same proportion as in 1990.
- Carbon dioxide emissions from incineration of waste (13.1 MMT CO_2 Eq. in 2020) increased slightly by 0.2 MMT CO_2 Eq. (1.5 percent) from 1990 through 2020, as the volume of scrap tires and other fossil C-containing materials in waste increased.

Industrial Processes and Product Use

Greenhouse gases can be generated and emitted by industry in two different ways. First, they are generated and emitted as the byproducts of many non-energy-related industrial activities. For example, industrial processes can chemically or physically transform raw materials, which often release waste gases such as CO_2, CH_4, N_2O, and fluorinated gases (e.g., HFC-23). In the case of byproduct emissions, the emissions are generated by an industrial process itself, and are not directly a result of energy consumed during the process.

Second, industrial manufacturing processes and use by end-consumers also release HFCs, PFCs, SF_6, and NF_3 and other fluorinated compounds. In addition to the use of HFCs and some PFCs as substitutes for ozone depleting substances (ODS), fluorinated compounds such as HFCs, PFCs, SF_6, NF_3, and others are also emitted through use by a number of other industrial sources in the United States. These industries include the electronics industry, electric power transmission and distribution, and magnesium metal production and processing. In addition, N_2O is used in and emitted by the electronics industry and anesthetic and aerosol applications, and CO_2 is consumed and emitted through various end-use applications.

Emission sources in the Industrial Processes and Product Use (IPPU) chapter accounted for 6.3 percent of U.S. greenhouse gas emissions in 2020. Emissions from the IPPU sector increased by 8.7 percent from 1990 to 2020. Total emissions from IPPU remained relatively constant between 2019 and 2020, decreasing 0.8 percent due to offsetting trends within the sector. Some industrial processes and product use categories experienced decreases due to impacts from the COVID-19 pandemic (e.g., Iron and Steel Production and Lime Production), while other categories experienced increases in emissions from 2019 to 2020 (e.g., Ammonia Production and the Substitution of Ozone Depleting Substances). Figure 2-8 presents greenhouse gas emissions from IPPU by source category.

Figure 2-8: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

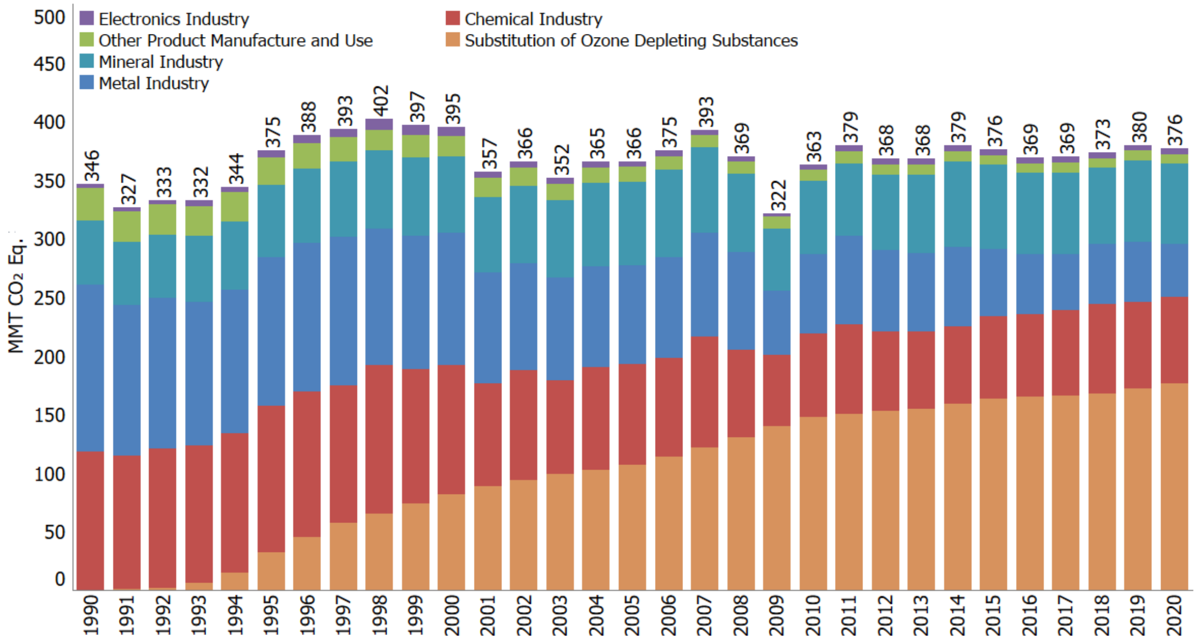


Table 2-6: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**213.0**	**194.4**	**166.0**	**164.7**	**165.1**	**171.2**	**163.6**
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	43.6	40.6	42.6	43.1	37.7
Iron and Steel Production	*99.1*	*66.2*	*41.0*	*38.6*	*41.3*	*40.1*	*35.4*
Metallurgical Coke Production	*5.6*	*3.9*	*2.6*	*2.0*	*1.3*	*3.0*	*2.3*
Cement Production	33.5	46.2	39.4	40.3	39.0	40.9	40.7
Petrochemical Production	21.6	27.4	28.1	28.9	29.3	30.7	30.0
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7
Lime Production	11.7	14.6	12.6	12.9	13.1	12.1	11.3
Other Process Uses of Carbonates	6.2	7.5	10.8	9.9	7.4	9.8	9.8
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	5.3	5.2	6.0	6.0	6.0
Carbon Dioxide Consumption	1.5	1.4	4.6	4.6	4.1	4.9	5.0
Glass Production	2.3	2.4	2.1	2.0	2.0	1.9	1.9
Aluminum Production	6.8	4.1	1.3	1.2	1.5	1.9	1.7
Soda Ash Production	1.4	1.7	1.7	1.8	1.7	1.8	1.5
Ferroalloy Production	2.2	1.4	1.8	2.0	2.1	1.6	1.4
Titanium Dioxide Production	1.2	1.8	1.7	1.7	1.5	1.5	1.3
Zinc Production	0.6	1.0	0.8	0.9	1.0	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	0.9	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.3**	**0.1**	**0.3**	**0.3**	**0.3**	**0.4**	**0.3**
Petrochemical Production	0.2	0.1	0.2	0.3	0.3	0.3	0.3
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Iron and Steel Production	+	+	+	+	+	+	+

Metallurgical Coke Production	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*	*NO*
N_2O	**33.3**	**24.9**	**23.4**	**22.7**	**26.0**	**21.1**	**23.3**
Nitric Acid Production	12.1	11.3	10.1	9.3	9.6	10.0	9.3
Adipic Acid Production	15.2	7.1	7.1	7.5	10.5	5.3	8.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.7	1.5	1.4	1.4	1.2
Electronics Industry	+	0.1	0.2	0.3	0.3	0.2	0.3
HFCs	**46.5**	**127.4**	**168.3**	**171.1**	**171.0**	**175.9**	**178.8**
Substitution of Ozone Depleting Substances[a]	0.2	107.2	165.1	165.5	167.3	171.8	176.2
HCFC-22 Production	46.1	20.0	2.8	5.2	3.3	3.7	2.1
Electronics Industry	0.2	0.2	0.3	0.4	0.4	0.4	0.4
Magnesium Production and Processing	NO	NO	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**4.4**	**4.2**	**4.8**	**4.6**	**4.4**
Electronics Industry	2.8	3.3	3.0	3.0	3.1	2.8	2.7
Aluminum Production	21.5	3.4	1.4	1.1	1.6	1.8	1.7
Substitution of Ozone Depleting Substances	NO	+	+	+	0.1	0.1	0.1
Electrical Transmission and Distribution	NO	+	+	+	NO	+	+
SF_6	**28.8**	**11.8**	**6.0**	**5.9**	**5.7**	**5.9**	**5.4**
Electrical Transmission and Distribution	23.2	8.3	4.1	4.2	3.8	4.2	3.8
Magnesium Production and Processing	5.2	2.7	1.1	1.0	1.0	0.9	0.9
Electronics Industry	0.5	0.7	0.8	0.7	0.8	0.8	0.7
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Total	**346.2**	**365.9**	**369.0**	**369.4**	**373.4**	**379.5**	**376.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from IPPU source categories over the thirty-one-year period from 1990 through 2020 included the following:

- HFC and PFC emissions resulting from the substitution of ODS (e.g., chlorofluorocarbons [CFCs]) have been increasing from small amounts in 1990 to 176.3 MMT CO_2 Eq. in 2020 and accounted for 46.8 percent of total IPPU emissions.
- Combined CO_2 and CH_4 emissions from iron and steel production and metallurgical coke production decreased by 12.4 percent from 2019 to 2020 to 37.7 MMT CO_2 Eq. and have declined overall by 67.0 MMT CO_2 Eq. (64.0 percent) from 1990 through 2020, due to restructuring of the industry. The trend in the United States has been a shift towards fewer integrated steel mills and more electric arc furnaces (EAFs). EAFs use scrap steel as their main input and generally have less on-site emissions.
- Carbon dioxide emissions from petrochemicals increased by 38.9 percent between 1990 and 2020 from 21.6 MMT CO_2 Eq. to 30.0 MMT CO_2 Eq. The increase in emissions is largely driven by a doubling of production of ethylene over that time period.
- Carbon dioxide emissions from ammonia production (12.7 MMT CO_2 Eq. in 2020) decreased by 2.5 percent (0.3 MMT CO_2 Eq.) since 1990. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia from year to year. Emissions from ammonia production have increased steadily since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities. Agricultural demands continue to drive demand for nitrogen fertilizers and the need for new ammonia production capacity.
- Carbon dioxide emissions from cement production increased by 21.5 percent (7.2 MMT CO_2 Eq.) from 1990 through 2020. They rose from 1990 through 2006 and then fell until 2009, due to a decrease in

demand for construction materials during the economic recession. Since 2010, CO_2 emissions from cement production have risen 29.4 percent (9.2 MMT CO_2 Eq.).

- Carbon dioxide emissions from lime production decreased by 6.7 percent (0.8 MMT CO_2) from 2019 to 2020. Compared to 1990, CO_2 emissions have decreased by about 3.4 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in lime production and since 2015, fluctuation in lime production has been driven by demand from the steel making industry.
- PFC emissions from aluminum production decreased by 92.2 percent (19.8 MMT CO_2 Eq.) from 1990 to 2020, due to both industry emission reduction efforts and lower domestic aluminum production.

Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes, including the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, liming, urea fertilization, and field burning of agricultural residues. Methane, N_2O, and CO_2 were the primary greenhouse gases emitted by agricultural activities. Carbon stock changes from agricultural soils are included in the LULUCF sector.

In 2020, agricultural activities were responsible for emissions of 594.7 MMT CO_2 Eq., or 9.9 percent of total U.S. greenhouse gas emissions. Methane emissions from enteric fermentation and manure management represented 26.9 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively, in 2020. Agricultural soil management activities, such as application of synthetic and organic fertilizers, deposition of livestock manure, and growing N-fixing plants, were the largest contributors to U.S. N_2O emissions in 2020, accounting for 74.2 percent. Carbon dioxide emissions from the application of crushed limestone and dolomite (i.e., soil liming) and urea fertilization represented 0.2 percent of total CO_2 emissions from anthropogenic activities. Figure 2-9 and Table 2-7 illustrate agricultural greenhouse gas emissions by source.

Figure 2-9: Trends in Agriculture Sector Greenhouse Gas Sources

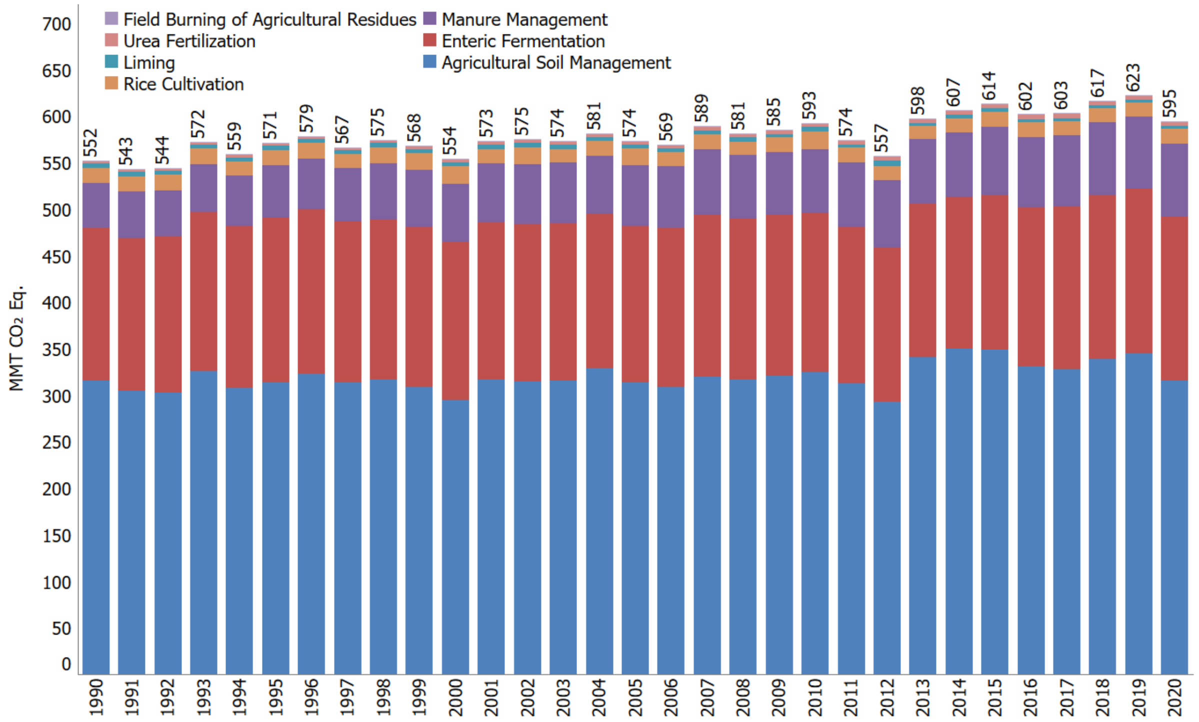


Table 2-7: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**7.1**	**7.9**	**7.8**	**8.0**	**7.3**	**7.6**	**7.7**
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3
Liming	4.7	4.3	3.1	3.1	2.2	2.4	2.4
CH_4	**214.7**	**235.5**	**244.7**	**247.8**	**251.1**	**250.3**	**250.9**
Enteric Fermentation	163.5	168.0	171.3	174.9	175.7	176.1	175.2
Manure Management	34.8	49.0	57.1	57.5	59.4	58.7	59.6
Rice Cultivation	16.0	18.0	15.8	14.9	15.6	15.1	15.7
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N_2O	**330.1**	**330.3**	**349.4**	**347.5**	**358.4**	**365.0**	**336.1**
Agricultural Soil Management	316.0	313.8	330.8	328.3	338.9	345.3	316.2
Manure Management	13.9	16.3	18.4	19.0	19.3	19.5	19.7
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.9**	**573.6**	**601.9**	**603.2**	**616.7**	**622.9**	**594.7**

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from Agriculture source categories (Figure 2-9) over the thirty-one-year period from 1990 through 2020 included the following:

- Agricultural soils are the largest anthropogenic source of N_2O emissions in the United States, accounting for 74.2 percent of N_2O emissions in 2020 and 5.3 percent of total emissions in the United States in 2020. Estimated emissions from this source in 2020 were 316.2 MMT CO_2 Eq. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2020, although overall emissions were only 0.2 MMT CO_2 Eq. or 0.1 percent higher in 2020 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production.

- Enteric fermentation is the largest anthropogenic source of CH_4 emissions in the United States. In 2020, enteric fermentation CH_4 emissions were 26.9 percent of total CH_4 emissions (175.2 MMT CO_2 Eq.), which represents an increase of 11.7 MMT CO_2 Eq. (7.2 percent) since 1990. This increase in emissions from 1990 to 2020 in enteric fermentation generally follows the increasing trends in cattle populations. For example, from 1990 to 1995, emissions increased and then generally decreased from 1996 to 2004, mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Emissions increased from 2005 to 2007, as both dairy and beef populations increased. Research indicates that the feed digestibility of dairy cow diets decreased during this period. Emissions decreased again from 2008 to 2014 as beef cattle populations again decreased. Emissions increased from 2014 to 2020, consistent with an increase in beef cattle population over those same years.

- Manure management emissions increased 62.5 percent between 1990 and 2020. This encompassed an increase of 71.0 percent for CH_4, from 34.8 MMT CO_2 Eq. in 1990 to 59.6 MMT CO_2 Eq. in 2020; and an increase of 41.2 percent for N_2O, from 13.9 MMT CO_2 Eq. in 1990 to 19.7 MMT CO_2 Eq. in 2020. The majority of the increase observed in CH_4 resulted from swine and dairy cattle manure, where emissions increased 44.2 and 122.0 percent, respectively, from 1990 to 2020. From 2019 to 2020, there was a 0.5 percent decrease in total CH_4 emissions from manure management, mainly due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

- Liming and urea fertilization are the only sources of CO_2 emissions reported in the Agriculture sector. All other CO_2 emissions and removals are characterized in the LULUCF sector. Estimated emissions from these sources were 2.4 and 5.3 MMT CO_2 Eq., respectively. Liming emissions decreased by 1.3 percent relative to 2019 and decreased 2.3 MMT CO_2 Eq. or 49.0 percent relative to 1990, while urea fertilization emissions increased by 2.6 percent relative to 2019 and 2.9 MMT CO_2 Eq. or 118.3 percent relative to 1990.

Land Use, Land-Use Change, and Forestry

When humans alter the terrestrial biosphere through land use, changes in land use, and land management practices, they also influence the carbon (C) stock fluxes on these lands and cause emissions of CH_4 and N_2O. Overall, managed land is a net sink for CO_2 (C sequestration) in the United States. The primary driver of fluxes on managed lands is from management of forest lands, but also includes trees in settlements (i.e., urban areas), afforestation, conversion of forest lands to settlements and croplands, the management of croplands and grasslands, flooded lands, and the landfilling of yard trimmings and food scraps. The main drivers for net forest sequestration include net forest growth, increasing forest area, and a net accumulation of C stocks in harvested wood pools. The net sequestration in *Settlements Remaining Settlements,* is driven primarily by C stock gains in urban forests (i.e., Settlement Trees) through net tree growth and increased urban area, as well as long-term accumulation of C in landfills from additions of yard trimmings and food scraps.

The LULUCF sector in 2020 resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.2 MMT CO_2 Eq. (Table 2-8).[3] This represents an offset of 13.6 percent of total (i.e., gross) greenhouse gas emissions in 2020. Emissions of CH_4 and N_2O from LULUCF activities in 2020 were 53.2 MMT CO_2 Eq. and represent 0.9 percent of total greenhouse gas emissions.[4] Between 1990 and 2020, total net C sequestration in the LULUCF sector decreased by 9.0 percent, primarily due to a decrease in the rate of net C accumulation in forests and *Cropland Remaining Cropland*, as well as an increase in CO_2 emissions from Land Converted to Settlements.

Flooded Land Remaining Flooded Land was the largest source of CH_4 emissions from LULUCF in 2020, totaling 19.9 MMT CO_2 Eq. (797 kt of CH_4). Forest fires were the second largest source of CH_4 emissions from LULUCF in 2020, totaling 13.6 MMT CO_2 Eq. (545 kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8 MMT CO_2 Eq. (154 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). Land Converted to Wetlands, Drained Organic Soils, and Peatlands Remaining Peatlands resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

Forest fires were the largest source of N_2O emissions from LULUCF in 2020, totaling 11.7 MMT CO_2 Eq. (39 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2020 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). Additionally, the application of synthetic fertilizers to forest soils in 2020 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* and Drained Organic Soils resulted in N_2O emissions of 0.2 MMT CO_2 Eq. each (0.5 kt of N_2O). Peatlands Remaining Peatland*s* resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq. Figure 2-10 and Table 2-8 along with CH_4 and N_2O emissions (purple) for LULUCF source categories.

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[3] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements*.*

[4] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from Flooded Land Remaining Flooded Land, Land Converted to Flooded Land, and *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 2-10: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

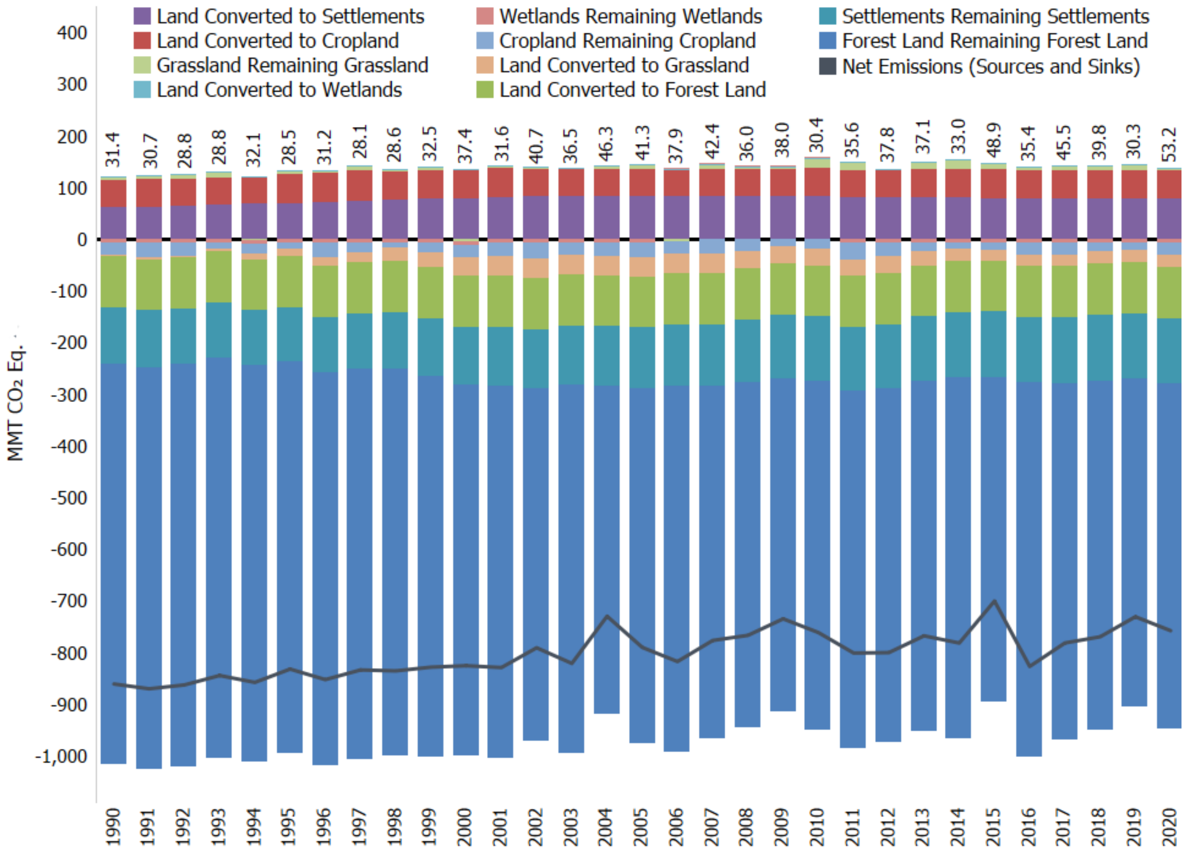

Table 2-8: U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Forest Land Remaining Forest Land	**(769.7)**	**(674.0)**	**(717.3)**	**(670.1)**	**(664.6)**	**(631.8)**	**(642.2)**
Changes in Forest Carbon Stocks[a]	(774.0)	(687.3)	(725.6)	(688.3)	(677.1)	(634.8)	(668.1)
Non-CO_2 Emissions from Forest Fires[b]	4.1	12.8	7.8	17.7	11.9	2.5	25.3
N_2O Emissions from Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.6)**	**(99.1)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**
Changes in Forest Carbon Stocks[e]	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	**(23.2)**	**(29.0)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**	**(23.3)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland	**51.8**	**52.0**	**54.1**	**54.3**	**54.0**	**53.9**	**54.4**
Changes in all Ecosystem Carbon Stocks[f]	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland	**7.1**	**9.4**	**8.6**	**9.9**	**10.3**	**13.1**	**5.1**
Changes in Mineral and Organic Soil Carbon Stocks	6.9	8.7	8.0	9.3	9.7	12.4	4.5
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.7	0.6	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(3.1)**	**(37.0)**	**(22.6)**	**(22.7)**	**(22.4)**	**(21.5)**	**(24.1)**
Changes in all Ecosystem Carbon Stocks[f]	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)

Wetlands Remaining Wetlands	**14.7**	**17.2**	**15.8**	**15.9**	**15.9**	**15.9**	**15.8**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.8	0.8	0.8	0.7
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.2	0.2	0.2
CH_4 Emissions from Flooded Land Remaining Flooded Land	18.2	19.8	19.9	19.9	19.9	19.9	19.9
Land Converted to Wetlands	**7.2**	**1.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.9	0.3	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.6	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(121.5)**	**(125.3)**	**(124.9)**	**(124.5)**	**(123.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	16.0	16.0	15.9	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(129.8)	(129.8)	(129.8)	(129.8)	(129.8)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.3	2.4	2.4	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(10.0)	(13.8)	(13.4)	(13.1)	(12.2)
Land Converted to Settlements	**60.8**	**82.8**	**77.8**	**77.9**	**78.0**	**77.9**	**77.9**
Changes in all Ecosystem Carbon Stocks[f]	60.8	82.8	77.8	77.9	78.0	77.9	77.9
LULUCF Emissions[i]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change[j]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[k]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.) and harvested wood products.

[b] Estimates include emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.* Carbon stock changes from drained organic soils are included with the *Forest Land Remaining Forest Land* forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements because it is not possible to separate the activity data at this time.

[i] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, *F*orest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from Flooded Land

Remaining Flooded Land, and Land Converted to Flooded Land, and *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Other significant trends from 1990 to 2020 in emissions from LULUCF categories (Figure 2-10) over the thirty-one-year period included the following:

- Annual carbon (C) sequestration by forest land (i.e., annual C stock accumulation in the five ecosystem C pools and harvested wood products for *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) has decreased by 12.0 percent since 1990. This is primarily due to decreased C stock gains in *Land Converted to Forest Land* and the harvested wood products pools within *Forest Land Remaining Forest Land*.
- Annual C sequestration from *Settlements Remaining Settlements* (which includes organic soils, settlement trees, and landfilled yard trimmings and food scraps) has increased by 15.1 percent over the period from 1990 to 2020. This is primarily due to an increase in urbanized land area in the United States with trees growing on it.
- Annual emissions from Land Converted to Settlements increased by 28.1 percent from 1990 to 2020 due primarily to C stock losses from Forest Land Converted to Settlements and mineral soils C stocks from Grassland Converted to Settlements.

Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 2-11 and Table 2-9). In 2020, landfills were the third-largest source of U.S. anthropogenic CH_4 emissions, generating 109.3 MMT CO_2 Eq. and accounting for 16.8 percent of total U.S. CH_4 emissions.[5] Additionally, wastewater treatment generates emissions of 41.8 MMT CO_2 Eq. and accounts for 26.9 percent of waste emissions, 2.8 percent of U.S. CH_4 emissions, and 5.5 percent of U.S. N_2O emissions. Emissions of CH_4 and N_2O from composting are also accounted for in this chapter, generating emissions of 2.3 MMT CO_2 Eq. and 2.0 MMT CO_2 Eq., respectively. Anaerobic digestion at biogas facilities generated CH_4 emissions of 0.2 MMT CO_2 Eq., accounting for 0.1 percent of emissions from the Waste sector. Overall, emission sources accounted for in the Waste chapter generated 155.6 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions in 2020.

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[5] Landfills also store carbon, due to incomplete degradation of organic materials such as wood products and yard trimmings, as described in the Land Use, Land-Use Change, and Forestry chapter.

Figure 2-11: Trends in Waste Sector Greenhouse Gas Sources

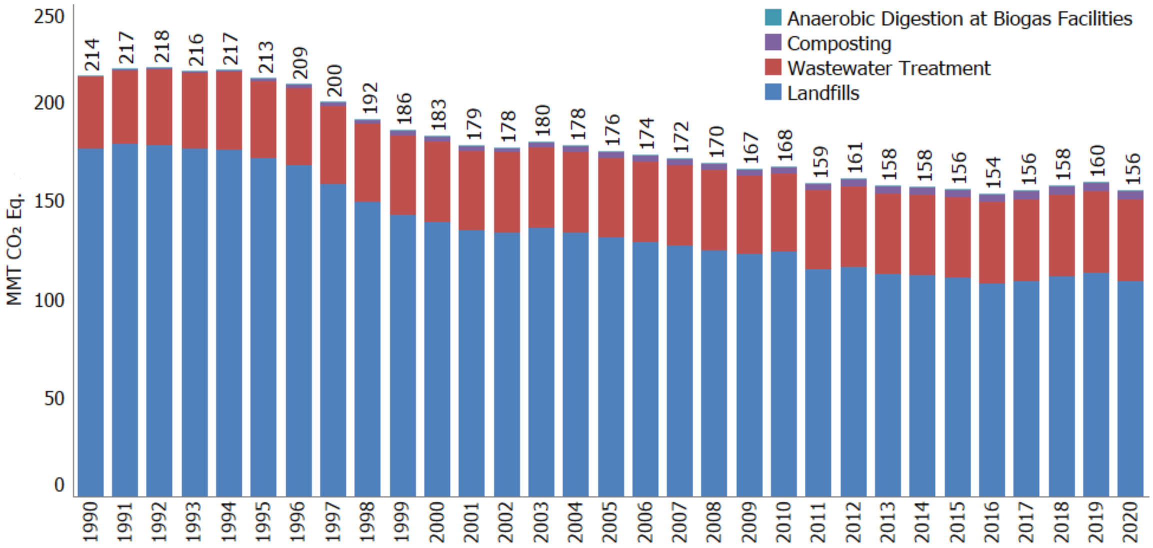


Table 2-9: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CH_4	**197.3**	**153.6**	**129.1**	**130.3**	**132.4**	**134.1**	**130.0**
Landfills	176.6	131.5	107.9	109.2	111.7	113.6	109.3
Wastewater Treatment	20.3	20.1	18.7	18.5	18.3	18.1	18.3
Composting	0.4	1.9	2.3	2.5	2.3	2.3	2.3
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2
N_2O	**16.9**	**22.0**	**24.8**	**25.4**	**25.5**	**25.4**	**25.6**
Wastewater Treatment	16.6	20.3	22.8	23.2	23.5	23.4	23.5
Composting	0.3	1.7	2.0	2.2	2.0	2.0	2.0
Total	**214.2**	**175.6**	**153.9**	**155.7**	**157.9**	**159.6**	**155.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Some significant trends in U.S. emissions from waste source categories (Figure 2-11) over the thirty-one-year period from 1990 through 2020 included the following:

- Net CH_4 emissions from landfills decreased by 67.2 MMT CO_2 Eq. (38.1 percent), with small increases occurring in interim years. This downward trend in emissions coincided with increased landfill gas collection and control systems, and a reduction of decomposable materials (i.e., paper and paperboard, food scraps, and yard trimmings) discarded in municipal solid waste (MSW) landfills over the time series.

- CH_4 and N_2O emissions from wastewater treatment decreased by 2.0 MMT CO_2 Eq. (10.0 percent) and increased by 6.9 MMT CO_2 Eq. (41.8 percent), respectively. Methane emissions from domestic wastewater treatment have decreased since 1999 due to decreasing percentages of wastewater being treated in anaerobic systems, including reduced use of on-site septic systems and central anaerobic treatment systems. Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption.

- Combined CH_4 and N_2O emissions from composting have generally increased 3.6 MMT CO_2 Eq. since 1990, from 0.7 MMT CO_2 Eq. to 4.3 MMT CO_2 Eq. in 2020, which represents more than a six-fold increase over the time series. The growth in composting since the 1990s is attributable to primarily four factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills; (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts; (3) an increased awareness of the environmental benefits of composting; and (4) loans or grant programs to establish or expand composting infrastructure.

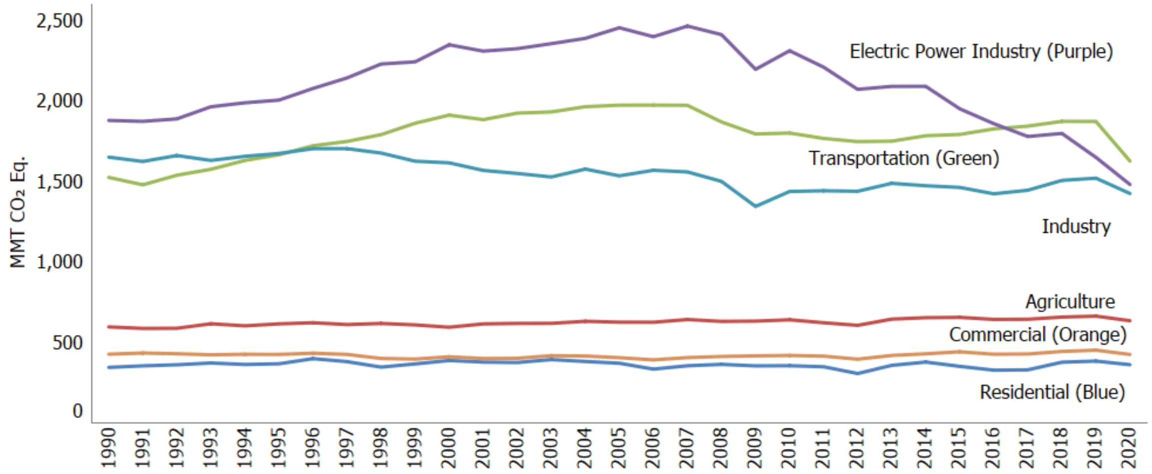
2.2 Emissions by Economic Sector

Throughout this report, emission estimates are grouped into five sectors (i.e., chapters) defined by the IPCC and detailed above: Energy, IPPU, Agriculture, LULUCF, and Waste. It is also useful to characterize emissions according to commonly used economic sector categories: residential, commercial, industry, transportation, electric power, and agriculture. Emissions from U.S. Territories are reported as their own end-use sector due to a lack of specific consumption data for the individual end-use sectors within U.S. Territories. See Box 2-1 for more information on how economic sectors are defined. For more information on trends in the Land Use, Land Use Change, and Forestry sector, see Section 2.1.

Using this categorization, transportation activities accounted for the largest portion (27.2 percent) of total U.S. greenhouse gas emissions in 2020. Emissions from electric power accounted for the second largest portion (24.8 percent), while emissions from industry accounted for the third largest portion (23.8 percent) of total U.S. greenhouse gas emissions in 2020. Emissions from industry have in general declined over the past decade due to a number of factors, including structural changes in the U.S. economy (i.e., shifts from a manufacturing-based to a service-based economy), fuel switching, and efficiency improvements.

The remaining 24.2 percent of U.S. greenhouse gas emissions were contributed by, in order of magnitude, the agriculture, commercial, and residential sectors, plus emissions from U.S. Territories. Activities related to agriculture accounted for roughly 10.6 percent of emissions; unlike other economic sectors, agricultural sector emissions were dominated by N_2O emissions from agricultural soil management and CH_4 emissions from enteric fermentation, rather than CO_2 from fossil fuel combustion. An increasing amount of carbon is stored in agricultural soils each year, but this CO_2 sequestration is assigned to the LULUCF sector rather than the agriculture economic sector. The commercial and residential sectors accounted for roughly 7.1 percent and 6.1 percent of greenhouse gas emissions, respectively, and U.S. Territories accounted for 0.4 percent of emissions; emissions from these sectors primarily consisted of CO_2 emissions from fossil fuel combustion. Carbon dioxide was also emitted and sequestered (in the form of C) by a variety of activities related to forest management practices, tree planting in urban areas, the management of agricultural soils, landfilling of yard trimmings, and changes in C stocks in coastal wetlands. Table 2-10 presents a detailed breakdown of emissions from each of these economic sectors by source category, as they are defined in this report. Figure 2-12 shows the trend in emissions by sector from 1990 to 2020.

Figure 2-12: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors



Note: Emissions and removals from Land Use, Land Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-10: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq. and Percent of Total in 2020)

Sector/Source	1990	2005	2016	2017	2018	2019	2020	Percent[a]
Transportation	**1,526.4**	**1,975.5**	**1,828.0**	**1,845.2**	**1,874.7**	**1,874.3**	**1,627.6**	**27.2%**
CO_2 from Fossil Fuel Combustion	1,468.9	1,858.6	1,757.6	1,780.0	1,812.8	1,813.8	1,572.0	26.3%
Substitution of Ozone Depleting Substances	+	69.3	43.3	40.1	38.5	36.7	35.0	0.6%
Mobile Combustion[b]	45.7	37.5	16.7	15.5	14.3	15.0	12.5	0.2%
Non-Energy Use of Fuels	11.8	10.2	10.4	9.6	9.2	8.8	8.0	0.1%
Electric Power Industry	**1,880.5**	**2,456.7**	**1,860.5**	**1,780.6**	**1,799.8**	**1,651.0**	**1,482.2**	**24.8%**
CO_2 from Fossil Fuel Combustion	1,820.0	2,400.1	1,808.9	1,732.0	1,752.9	1,606.1	1,439.0	24.1%
Stationary Combustion[b]	20.9	30.9	27.4	25.9	25.6	22.3	21.0	0.4%
Incineration of Waste	13.4	13.7	14.8	13.6	13.8	13.4	13.5	0.2%
Other Process Uses of Carbonates	3.1	3.7	5.4	4.9	3.7	4.9	4.9	0.1%
Electrical Transmission and Distribution	23.2	8.4	4.1	4.2	3.8	4.2	3.8	0.1%
Industry	**1,652.4**	**1,536.2**	**1,424.4**	**1,446.7**	**1,507.6**	**1,521.7**	**1,426.2**	**23.8%**
CO_2 from Fossil Fuel Combustion	810.3	800.7	752.6	750.6	774.3	776.4	727.2	12.2%
Natural Gas Systems	227.4	202.5	195.0	197.7	204.2	210.9	200.3	3.3%
Non-Energy Use of Fuels	97.0	111.2	88.4	102.8	119.4	117.7	112.7	1.9%
Petroleum Systems	57.4	53.4	62.3	65.6	75.9	87.1	70.4	1.2%
Coal Mining	101.1	68.3	56.7	57.9	55.8	50.3	43.4	0.7%
Cement Production	33.5	46.2	39.4	40.3	39.0	40.9	40.7	0.7%
Iron and Steel Production	104.8	70.1	43.6	40.6	42.6	43.1	37.7	0.6%
Substitution of Ozone Depleting Substances	+	8.6	29.9	32.4	34.4	35.7	36.5	0.6%
Petrochemical Production	21.8	27.5	28.4	29.1	29.6	31.0	30.3	0.5%
Landfills (Industrial)	10.9	14.4	15.0	15.0	15.0	15.1	15.1	0.3%
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7	0.2%
Lime Production	11.7	14.6	12.6	12.9	13.1	12.1	11.3	0.2%
Nitric Acid Production	12.1	11.3	10.1	9.3	9.6	10.0	9.3	0.2%
Adipic Acid Production	15.2	7.1	7.1	7.5	10.5	5.3	8.3	0.1%
Wastewater Treatment	6.0	6.5	6.6	6.7	6.8	6.9	6.9	0.1%
Abandoned Oil and Gas Wells	6.5	6.8	6.9	6.9	6.9	7.0	6.9	0.1%
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	5.3	5.2	6.0	6.0	6.0	0.1%
Abandoned Underground Coal Mines	7.2	6.6	6.7	6.4	6.2	5.9	5.8	0.1%
Mobile Combustion[b]	3.9	6.1	5.6	5.8	6.0	6.1	5.7	0.1%
Carbon Dioxide Consumption	1.5	1.4	4.6	4.6	4.1	4.9	5.0	0.1%
Other Process Uses of Carbonates	3.1	3.7	5.4	4.9	3.7	4.9	4.9	0.1%
Electronics Industry	3.6	4.8	5.0	4.9	5.1	4.7	4.7	0.1%
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2	0.1%
Stationary Combustion[b]	4.9	4.7	4.2	4.1	4.0	4.0	3.7	+%
Aluminum Production	28.3	7.6	2.7	2.3	3.1	3.6	3.4	0.1%
HCFC-22 Production	46.1	20.0	2.8	5.2	3.3	3.7	2.1	0.1%
Glass Production	2.3	2.4	2.1	2.0	2.0	1.9	1.9	+%
Soda Ash Production	1.4	1.7	1.7	1.8	1.7	1.8	1.5	+%
Ferroalloy Production	2.2	1.4	1.8	2.0	2.1	1.6	1.4	+%
Titanium Dioxide Production	1.2	1.8	1.7	1.7	1.5	1.5	1.3	+%

Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.7	1.5	1.4	1.4	1.2	+%
Zinc Production	0.6	1.0	0.8	0.9	1.0	1.0	1.0	+%
Phosphoric Acid Production	1.5	1.3	1.0	1.0	0.9	0.9	0.9	+%
Magnesium Production and Processing	5.3	2.7	1.2	1.1	1.1	0.9	0.9	+%
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5	+%
Carbide Production and Consumption	0.3	0.2	0.2	0.2	0.2	0.2	0.2	+%
Agriculture	**596.8**	**626.3**	**643.4**	**644.4**	**657.9**	**663.9**	**635.1**	**10.6%**
N_2O from Agricultural Soil Management	316.0	313.8	330.8	328.3	338.9	345.3	316.2	5.3%
Enteric Fermentation	163.5	168.0	171.3	174.9	175.7	176.1	175.2	2.9%
Manure Management	48.8	65.3	75.5	76.5	78.7	78.2	79.2	1.3%
CO_2 from Fossil Fuel Combustion	43.4	50.8	40.2	39.8	39.8	39.7	39.1	0.7%
Rice Cultivation	16.0	18.0	15.8	14.9	15.6	15.1	15.7	0.3%
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3	0.1%
Liming	4.7	4.3	3.1	3.1	2.2	2.4	2.4	+%
Mobile Combustion[b]	1.5	1.8	1.4	1.4	1.4	1.4	1.3	+%
Field Burning of Agricultural Residues	0.5	0.6	0.6	0.6	0.6	0.6	0.6	+%
Stationary Combustion[b]	+	+	+	+	+	+	+	+%
Commercial	**427.1**	**405.4**	**426.9**	**428.5**	**444.2**	**452.1**	**425.3**	**7.1%**
CO_2 from Fossil Fuel Combustion	228.3	227.1	231.5	232.0	245.8	250.7	226.8	3.8%
Landfills (Municipal)	165.7	117.2	93.0	94.2	96.7	98.6	94.2	1.6%
Substitution of Ozone Depleting Substances	+	22.1	61.5	61.0	60.8	62.3	63.5	1.1%
Wastewater Treatment	30.9	34.0	34.9	35.0	35.0	34.5	34.8	0.6%
Composting	0.7	3.5	4.3	4.6	4.3	4.3	4.3	0.1%
Stationary Combustion[b]	1.5	1.4	1.5	1.5	1.6	1.6	1.5	+%
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2	+%
Residential	**345.1**	**371.0**	**327.8**	**329.9**	**377.4**	**384.2**	**362.0**	**6.1%**
CO_2 from Fossil Fuel Combustion	338.6	358.9	292.8	293.4	338.2	341.4	315.8	5.3%
Substitution of Ozone Depleting Substances	0.2	7.2	30.4	31.9	33.7	37.1	41.2	0.7%
Stationary Combustion[b]	6.3	4.9	4.7	4.5	5.5	5.7	4.9	0.1%
U.S. Territories	**25.1**	**63.7**	**26.8**	**25.8**	**25.8**	**24.6**	**23.0**	**0.4%**
CO_2 from Fossil Fuel Combustion	21.7	55.9	26.0	25.5	25.5	24.3	22.7	0.4%
Non-Energy Use of Fuels	3.4	7.6	0.7	0.2	0.2	0.2	0.2	+%
Stationary Combustion[b]	0.1	0.2	0.1	0.1	0.1	0.1	0.1	+%
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**	**100.0%**
LULUCF Sector Net Total[c]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**	**(12.7%)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**	**87.3%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for 2020.

[b] Includes CH_4 and N_2O emissions from fuel combustion.

[c] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions presented without LULUCF. Total net emissions presented with LULUCF. Totals may not sum due to independent rounding. Parentheses indicate negative values or sequestration.

Box 2-1: Methodology for Aggregating Emissions by Economic Sector

In presenting the Economic Sectors in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the Inventory expands upon the standard IPCC sectors common for UNFCCC reporting. Discussing greenhouse gas emissions relevant to U.S.-specific economic sectors improves communication of the report's findings.

The *Electric Power* economic sector includes CO_2, CH_4 and N_2O emissions from the combustion of fossil fuels that are included in the EIA electric power sector. Carbon dioxide, CH_4, and N_2O emissions from waste incineration are included in the Electric Power economic sector, as the majority of municipal solid waste is combusted in plants that produce electricity. The Electric Power economic sector also includes SF_6 from Electrical Transmission and Distribution, and a portion of CO_2 from Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

The *Transportation* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA transportation fuel-consuming sector. (Additional analyses and refinement of the EIA data are further explained in the Energy chapter of this report.) Emissions of CH_4 and N_2O from mobile combustion are also apportioned to the Transportation economic sector based on the EIA transportation fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Transportation economic sector based on emissions from refrigerated transport and motor vehicle air-conditioning systems. Finally, CO_2 emissions from Non-Energy Uses of Fossil Fuels identified as lubricants for transportation vehicles are included in the Transportation economic sector.

The *Industry* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA industrial fuel-consuming sector, minus the agricultural use of fuel explained below. The CH_4 and N_2O emissions from stationary and mobile combustion are also apportioned to the Industry economic sector based on the EIA industrial fuel-consuming sector, minus emissions apportioned to the Agriculture economic sector. Substitution of Ozone Depleting Substances emissions are apportioned based on their specific end-uses within the source category, with most emissions falling within the Industry economic sector. Finally, CH_4 emissions from industrial landfills and CH_4 and N_2O from industrial wastewater treatment are included in the Industry economic sector.

Additionally, all process-related emissions from sources with methods considered within the IPCC IPPU sector are apportioned to the Industry economic sector. This includes the process-related emissions (i.e., emissions from the actual process to make the material, not from fuels to power the plant) from activities such as Cement Production, Iron and Steel Production and Metallurgical Coke Production, and Ammonia Production. Additionally, fugitive emissions from energy production sources, such as Natural Gas Systems, Coal Mining, and Petroleum Systems are included in the Industry economic sector. A portion of CO_2 from Other Process Uses of Carbonates (from pollution control equipment installed in large industrial facilities) is also included in the Industry economic sector. Finally, all remaining CO_2 emissions from Non-Energy Uses of Fossil Fuels are assumed to be industrial in nature (besides the lubricants for transportation vehicles specified above) and are attributed to the Industry economic sector.

The *Agriculture* economic sector includes CO_2 emissions from the combustion of fossil fuels that are based on supplementary sources of agriculture fuel use data, because EIA includes agriculture equipment in the industrial fuel-consuming sector. Agriculture fuel use estimates are obtained from U.S. Department of Agriculture survey data, in combination with EIA Fuel Oil and Kerosene Sales (FOKS) data (EIA 1991 through 2021). Agricultural operations are based on annual energy expense data from the Agricultural Resource Management Survey (ARMS) conducted by the National Agricultural Statistics Service (NASS) of the USDA. NASS collects information on farm production expenditures including expenditures on diesel fuel, gasoline, LP gas, natural gas, and electricity use on the farm with the annual ARMS. A USDA publication (USDA/NASS 2020) shows national totals, as well as select States and ARMS production regions. These supplementary data are subtracted from the industrial fuel use reported by EIA to obtain agriculture fuel use. CO_2 emissions from fossil fuel combustion, and CH_4 and N_2O emissions from stationary and mobile combustion, are then apportioned to the Agriculture economic sector based on agricultural fuel use.

The other IPCC Agriculture emission source categories apportioned to the Agriculture economic sector include

N_2O emissions from Agricultural Soils, CH_4 from Enteric Fermentation, CH_4 and N_2O from Manure Management, CH_4 from Rice Cultivation, CO_2 emissions from Liming and Urea Application, and CH_4 and N_2O from Field Burning of Agricultural Residues.

The *Residential* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA residential fuel-consuming sector. Stationary combustion emissions of CH_4 and N_2O are also based on the EIA residential fuel-consuming sector. Substitution of Ozone Depleting Substances are apportioned to the Residential economic sector based on emissions from residential air-conditioning systems. Nitrous oxide emissions from the application of fertilizers to developed land (termed “settlements” by the IPCC) are also included in the Residential economic sector.

The *Commercial* economic sector includes CO_2 emissions from the combustion of fossil fuels that are included in the EIA commercial fuel-consuming sector. Emissions of CH_4 and N_2O from Mobile Combustion are also apportioned to the Commercial economic sector based on the EIA commercial fuel-consuming sector. Substitution of Ozone Depleting Substances emissions are apportioned to the Commercial economic sector based on emissions from commercial refrigeration/air-conditioning systems. Public works sources, including direct CH_4 from municipal landfills, CH_4 from anaerobic digestion at biogas facilities, CH_4 and N_2O from domestic wastewater treatment, and composting, are also included in the Commercial economic sector.

Emissions with Electricity Distributed to Economic Sectors

It is also useful to view greenhouse gas emissions from economic sectors with emissions related to electric power distributed into end-use categories (i.e., emissions from electric power are allocated to the economic sectors in which the electricity is used).

The generation, transmission, and distribution of electricity accounted for 24.8 percent of total U.S. greenhouse gas emissions in 2020. Electric power-related emissions decreased by 21.2 percent since 1990 and by 10.2 percent from 2019 to 2020, due to the impacts of the COVID-19 pandemic in 2020 compared to 2019 and continued fuel switching in the electric power sector. Between 2019 to 2020, the consumption of natural gas for electric power generation increased by 2.9, while the consumption of coal and petroleum decreased by 19.2 and 2.2 percent, respectively, reflecting a continued shift from coal to natural gas for electricity generation.

From 2019 to 2020, electricity sales to the residential end-use sector increased by 1.7 percent. Alternatively, electricity sales to the commercial end-use and industrial sectors decreased by 5.4 percent and 4.3 percent, respectively. Overall, from 2019 to 2020, the amount of electricity retail sales (in kWh) decreased by 2.5 percent. Table 2-11 provides a detailed summary of emissions from electric power-related activities.

Table 2-11: Electric Power-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Fuel Type or Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**1,836.0**	**2,417.1**	**1,828.6**	**1,750.1**	**1,770.0**	**1,624.0**	**1,457.0**
Fossil Fuel Combustion	1,820.0	2,400.1	1,808.9	1,732.0	1,752.9	1,606.1	1,439.0
Coal	*1,546.5*	*1,982.8*	*1,242.0*	*1,207.1*	*1,152.9*	*973.5*	*788.2*
Natural Gas	*175.4*	*318.9*	*545.0*	*505.6*	*577.4*	*616.0*	*634.3*
Petroleum	*97.5*	*98.0*	*21.5*	*18.9*	*22.2*	*16.2*	*16.2*
Geothermal	*0.5*	*0.5*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Incineration of Waste	12.9	13.3	14.4	13.2	13.3	12.9	13.1
Other Process Uses of Carbonates	3.1	3.7	5.4	4.9	3.7	4.9	4.9
CH_4	**0.4**	**0.9**	**1.2**	**1.1**	**1.2**	**1.3**	**1.2**
Stationary Sources[a]	0.4	0.9	1.2	1.1	1.2	1.3	1.2
Incineration of Waste	+	+	+	+	+	+	+
N_2O	**21.0**	**30.4**	**26.6**	**25.2**	**24.8**	**21.5**	**20.1**
Stationary Sources[a]	20.5	30.1	26.2	24.8	24.4	21.1	19.7
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
SF_6	**23.2**	**8.3**	**4.1**	**4.2**	**3.8**	**4.2**	**3.8**
Electrical Transmission and Distribution	23.2	8.3	4.1	4.2	3.8	4.2	3.8
PFCs	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	+	+	+	+	+	+	+
Total	**1,880.5**	**2,456.7**	**1,860.5**	**1,780.6**	**1,799.8**	**1,651.0**	**1,482.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Includes only stationary combustion emissions related to the generation of electricity.

Note: Totals may not sum due to independent rounding.

To distribute electricity emissions among economic end-use sectors, emissions from the source categories assigned to the electric power sector were allocated to the residential, commercial, industry, transportation, and agriculture economic sectors according to each economic sector's share of retail sales of electricity (EIA 2020b; USDA/NASS 2020). These source categories include CO_2 from Fossil Fuel Combustion, CH_4 and N_2O from Stationary Combustion, Incineration of Waste, Other Process Uses of Carbonates, and SF_6 from Electrical Transmission and Distribution Systems. Note that only 50 percent of the Other Process Uses of Carbonates emissions were associated with electric power and distributed as described; the remainder of Other Process Uses of Carbonates emissions were attributed to the industrial processes economic end-use sector.[6]

When emissions from electricity use are distributed among these economic end-use sectors, industrial activities account for the largest share of total U.S. greenhouse gas emissions (30.3 percent), followed closely by emissions from transportation (27.3 percent). Emissions from the residential and commercial sectors also increase substantially when emissions from electricity are included (both 15.4 percent). In all economic end-use sectors except agriculture, CO_2 accounts for more than 77.5 percent of greenhouse gas emissions, primarily from the combustion of fossil fuels. Table 2-12 presents a detailed breakdown of emissions from each of these economic sectors, with emissions from electric power distributed to them. Figure 2-13 shows the trend in these emissions by sector from 1990 to 2020.

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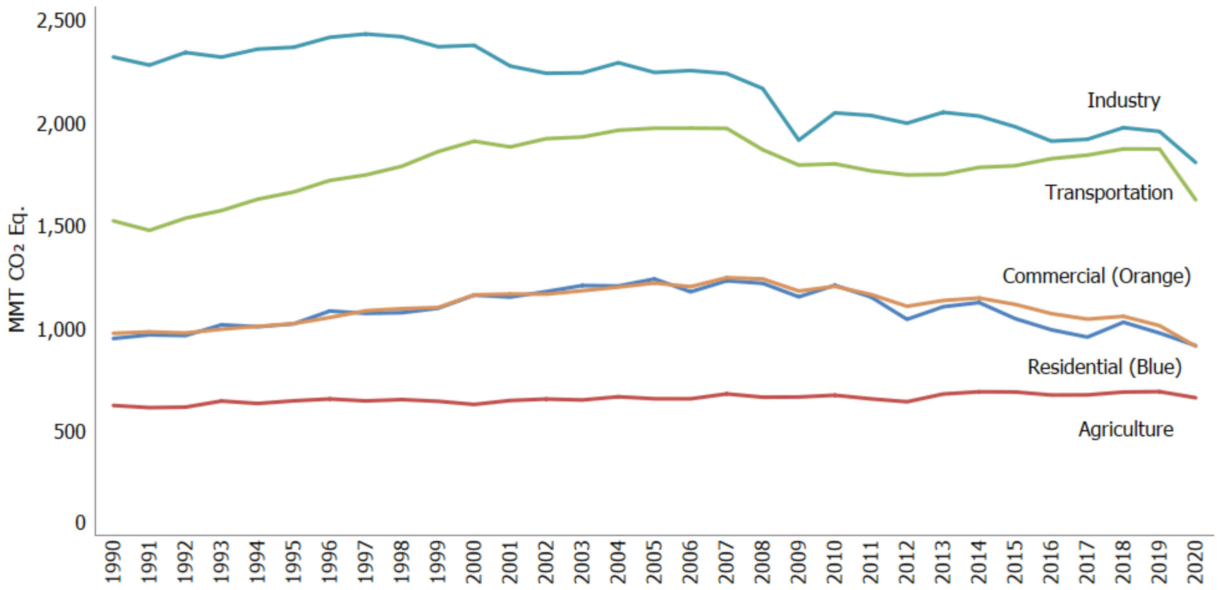
[6] Emissions were not distributed to U.S. Territories, since the electric power sector only includes emissions related to the generation of electricity in the 50 states and the District of Columbia.

Figure 2-13: U.S. Greenhouse Gas Emissions with Electricity-Related Emissions Distributed to Economic Sectors



Note: Emissions and removals from Land Use, Land-Use Change, and Forestry are excluded from figure above. Excludes U.S. Territories.

Table 2-12: U.S. Greenhouse Gas Emissions by Economic Sector and Gas with Electricity-Related Emissions Distributed (MMT CO_2 Eq.) and Percent of Total in 2020

Sector/Gas	1990	2005	2016	2017	2018	2019	2020	Percent[a]
Industry	**2,326.5**	**2,251.6**	**1,917.5**	**1,926.4**	**1,983.1**	**1,964.7**	**1,813.7**	**30.3%**
Direct Emissions	**1,652.4**	**1,536.2**	**1,424.4**	**1,446.7**	**1,507.6**	**1,521.7**	**1,426.2**	**23.8%**
CO_2	1,163.3	1,143.6	1,056.1	1,072.4	1,127.9	1,148.8	1,066.3	17.8%
CH_4	372.7	319.5	296.8	299.1	300.3	297.0	283.2	4.7%
N_2O	40.1	33.6	31.3	30.7	34.1	29.3	31.0	0.5%
HFCs, PFCs, SF_6 and NF_3	76.3	39.5	40.1	44.4	45.3	46.6	45.6	0.8%
Electricity-Related	**674.1**	**715.4**	**493.2**	**479.7**	**475.4**	**443.1**	**387.5**	**6.5%**
CO_2	658.1	703.8	484.7	471.5	467.6	435.8	380.9	6.4%
CH_4	0.2	0.3	0.3	0.3	0.3	0.3	0.3	+%
N_2O	7.5	8.9	7.1	6.8	6.6	5.8	5.3	0.1%
SF_6	8.3	2.4	1.1	1.1	1.0	1.1	1.0	+%
Transportation	**1,529.6**	**1,980.3**	**1,832.4**	**1,849.6**	**1,879.5**	**1,879.1**	**1,632.4**	**27.3%**
Direct Emissions	**1,526.4**	**1,975.5**	**1,828.0**	**1,845.2**	**1,874.7**	**1,874.3**	**1,627.6**	**27.2%**
CO_2	1,480.8	1,868.7	1,768.0	1,789.5	1,822.0	1,822.6	1,580.1	26.4%
CH_4	5.7	2.9	1.6	1.5	1.4	1.4	1.2	+%
N_2O	39.9	34.5	15.1	14.0	12.9	13.5	11.3	0.2%
HFCs[b]	+	69.3	43.3	40.1	38.5	36.7	35.0	0.6%
Electricity-Related	**3.1**	**4.8**	**4.3**	**4.4**	**4.8**	**4.9**	**4.8**	**0.1%**
CO_2	3.1	4.8	4.2	4.3	4.7	4.8	4.7	0.1%
CH_4	+	+	+	+	+	+	+	+%
N_2O	+	0.1	0.1	0.1	0.1	0.1	0.1	+%
SF_6	+	+	+	+	+	+	+	+%
Residential	**957.6**	**1,247.2**	**999.9**	**964.3**	**1,036.7**	**984.1**	**923.1**	**15.4%**
Direct Emissions	**345.1**	**371.0**	**327.8**	**329.9**	**377.4**	**384.2**	**362.0**	**6.1%**
CO_2	338.6	358.9	292.8	293.4	338.2	341.4	315.8	5.3%
CH_4	5.2	4.1	3.9	3.8	4.6	4.7	4.1	0.1%
N_2O	1.0	0.9	0.8	0.8	0.9	0.9	0.8	+%

SF_6	0.2	7.2	30.4	31.9	33.7	37.1	41.2	0.7%
Electricity-Related	**612.5**	**876.2**	**672.1**	**634.4**	**659.4**	**599.9**	**561.1**	**9.4%**
CO_2	598.0	862.1	660.6	623.6	648.4	590.1	551.6	9.2%
CH_4	0.1	0.3	0.4	0.4	0.4	0.5	0.5	+%
N_2O	6.8	10.9	9.6	9.0	9.1	7.8	7.6	0.1%
SF_6	7.5	3.0	1.5	1.5	1.4	1.5	1.4	+%
Commercial	**982.7**	**1,227.4**	**1,078.6**	**1,051.7**	**1,065.3**	**1,020.1**	**919.7**	**15.4%**
Direct Emissions	**427.1**	**405.4**	**426.9**	**428.5**	**444.2**	**452.1**	**425.3**	**7.1%**
CO_2	228.3	227.1	231.5	232.0	245.8	250.7	226.8	3.8%
CH_4	181.9	134.3	109.2	110.3	112.3	113.9	109.6	1.8%
N_2O	16.9	21.8	24.6	25.2	25.3	25.3	25.4	0.4%
HFCs	+	22.1	61.5	61.0	60.8	62.3	63.5	1.1%
Electricity-Related	**555.6**	**822.0**	**651.7**	**623.2**	**621.1**	**567.9**	**494.4**	**8.3%**
CO_2	542.5	808.7	640.6	612.6	610.8	558.6	486.0	8.1%
CH_4	0.1	0.3	0.4	0.4	0.4	0.4	0.4	+%
N_2O	6.2	10.2	9.3	8.8	8.6	7.4	6.7	0.1%
SF_6	6.8	2.8	1.4	1.5	1.3	1.5	1.3	+%
Agriculture	**631.9**	**664.6**	**682.6**	**683.2**	**697.1**	**699.1**	**669.5**	**11.2%**
Direct Emissions	**596.8**	**626.3**	**643.4**	**644.4**	**657.9**	**663.9**	**635.1**	**10.6%**
CO_2	50.5	58.7	47.9	47.8	47.1	47.2	46.7	0.8%
CH_4	214.8	235.7	244.8	247.9	251.2	250.5	251.0	4.2%
N_2O	331.5	331.9	350.7	348.7	359.6	366.2	337.3	5.6%
Electricity-Related	**35.2**	**38.3**	**39.2**	**38.8**	**39.2**	**35.2**	**34.4**	**0.6%**
CO_2	34.3	37.7	38.5	38.1	38.5	34.6	33.8	0.6%
CH_4	+	+	+	+	+	+	+	+%
N_2O	0.4	0.5	0.6	0.5	0.5	0.5	0.5	+%
SF_6	0.4	0.1	0.1	0.1	0.1	0.1	0.1	+%
U.S. Territories	**25.1**	**63.7**	**26.8**	**25.8**	**25.8**	**24.6**	**23.0**	**0.4%**
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**	**100.0%**
LULUCF Sector Net Total[c]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**	**(12.7%)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**	**87.3%**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

[a] Percent of total (gross) emissions excluding emissions from LULUCF for year 2020.

[b] Includes primarily HFC-134a.

[c] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Notes: Total emissions presented without LULUCF. Net emissions presented with LULUCF. Emissions from electric power are allocated based on aggregate electricity use in each end-use sector. Totals may not sum due to independent rounding.

Industry

The industry end-use sector includes CO_2 emissions from fossil fuel combustion from all manufacturing facilities, in aggregate, and with the distribution of electricity-related emissions, accounts for 30.3 percent of U.S. greenhouse gas emissions in 2020. This end-use sector also includes emissions that are produced as a byproduct of the non-energy-related industrial process activities. The variety of activities producing these non-energy-related emissions includes CH_4 emissions from petroleum and natural gas systems, fugitive CH_4 and CO_2 emissions from coal mining, byproduct CO_2 emissions from cement manufacture, and HFC, PFC, SF_6, and NF_3 byproduct emissions from the electronics industry, to name a few.

Since 1990, industrial sector emissions have declined by 22.0 percent. The decline has occurred both in direct emissions and indirect emissions associated with electricity use. Structural changes within the U.S. economy that led to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

Transportation

When electricity-related emissions are distributed to economic end-use sectors, transportation activities accounted for 27.2 percent of U.S. greenhouse gas emissions in 2020. The largest sources of transportation greenhouse gas emissions in 2020 were passenger cars (37.8 percent); freight trucks (25.9 percent); light-duty trucks, which include sport utility vehicles, pickup trucks, and minivans (19.3 percent); commercial aircraft (5.6 percent); pipelines (3.5 percent); rail (2.1 percent); ships and boats (2.0 percent); and other aircraft (1.9 percent). These figures include direct CO_2, CH_4, and N_2O emissions from fossil fuel combustion used in transportation, indirect emissions from electricity use, and emissions from non-energy use (i.e., lubricants) used in transportation, as well as HFC emissions from mobile air conditioners and refrigerated transport allocated to these vehicle types.

From 1990 to 2020, total transportation emissions from fossil fuel combustion increased by approximately 4.8 percent. From 1990 to 2019, emissions increased by 20.9 percent, followed by a decline of 13.3 percent from 2019 to 2020. The increase in transportation emissions from 1990 to 2019 was due, in large part, to increased demand for travel. The number of VMT by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47.5 percent from 1990 to 2019, as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices. The drop in transportation emissions from 2019 to 2020 was primarily the result of less travel caused by the COVID-19 pandemic. During this period, the number of VMT by light-duty motor vehicles decreased by 12.2 percent.

The decline in new light-duty vehicle fuel economy between 1990 and 2004 reflected the increasing market share of light-duty trucks, which grew from approximately 29.6 percent of new vehicle sales in 1990 to 48.0 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty VMT grew only modestly for much of the period. Light-duty VMT grew by less than one percent or declined each year between 2005 and 2013,[7] then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Since 2016, the rate of light-duty VMT growth has slowed to at or less than one percent each year. Average new vehicle fuel economy has increased almost every year since 2005, while light-duty truck market share decreased to 33.0 percent in 2009 and has since varied from year to year between 35.6 and 56.1 percent. Light-duty truck market share was about 56.1 percent of new vehicles in model year 2020 (EPA 2021a).

Table 2-13 provides a detailed summary of greenhouse gas emissions from transportation-related activities with electricity-related emissions included in the totals. Historically, the majority of electricity use in the transportation sector was for rail transport. However, more recently there has been increased electricity use in on-road electric and plug-in hybrid vehicles. For a more detailed breakout of emissions by fuel type by vehicle see Table A-99 in Annex 3.

Almost all of the energy used for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 7.0 percent from 1990 to 2020.[8] This rise in CO_2 emissions, combined with an increase in HFCs from close to zero emissions in 1990 to 35.0 MMT CO_2 Eq. in 2020, led to an increase in overall greenhouse gas emissions from transportation activities of 6.7 percent.[9]

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[7] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). In 2007 and 2008 light-duty VMT decreased 3.9 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2018 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

[8] See previous footnote.

[9] See previous footnote.

Figure 2-14: Trends in Transportation-Related Greenhouse Gas Emissions[10]

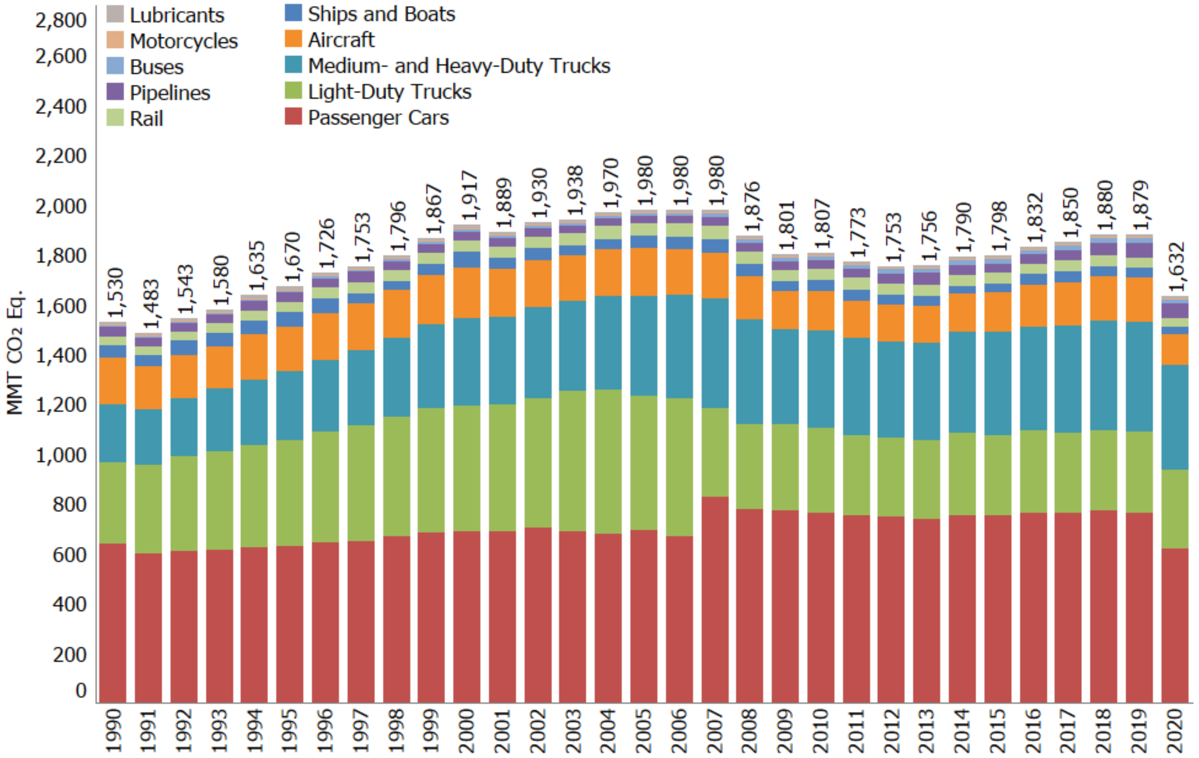

Table 2-13: Transportation-Related Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Vehicle	1990	2005	2016	2017	2018	2019	2020
Passenger Cars	**639.6**	**691.7**	**763.2**	**760.6**	**770.2**	**763.1**	**617.7**
CO_2	612.2	641.4	742.4	742.5	754.2	748.0	605.0
CH_4	3.2	1.3	0.6	0.5	0.5	0.5	0.4
N_2O	24.1	17.3	7.1	6.1	5.1	5.3	3.9
HFCs	0.0	31.7	13.2	11.4	10.4	9.3	8.3
Light-Duty Trucks	**326.7**	**537.7**	**330.0**	**324.3**	**325.6**	**323.7**	**315.8**
CO_2	312.2	490.0	305.8	302.4	305.2	304.0	297.8
CH_4	1.7	0.8	0.2	0.2	0.2	0.2	0.2
N_2O	12.8	13.6	2.9	2.4	2.1	2.5	2.2
HFCs	0.0	33.3	21.1	19.2	18.1	16.9	15.6
Medium- and Heavy-Duty Trucks	**230.3**	**404.1**	**416.8**	**429.7**	**440.0**	**439.5**	**422.8**
CO_2	229.3	399.4	408.2	420.8	430.7	429.9	412.9
CH_4	0.3	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.7	1.2	2.9	3.1	3.3	3.4	3.4
HFCs	0.0	3.4	5.5	5.7	5.9	6.1	6.3
Buses	**8.5**	**12.3**	**19.0**	**20.5**	**21.8**	**21.7**	**18.0**
CO_2	8.4	11.8	18.4	19.8	21.1	21.1	17.4

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[10] In 2011 FHWA changed its methods for estimating VMT and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2008 Inventory and apply to the 2007 to 2020 time period. This resulted in large changes in VMT data by vehicle class, leading to a shift in emissions among on-road vehicle classes. This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this Inventory.

CH_4	+	0.2	0.1	0.1	0.1	0.1	+
N_2O	+	+	0.1	0.1	0.2	0.2	0.1
HFCs	0.0	0.3	0.4	0.4	0.4	0.4	0.4
Motorcycles	**1.7**	**1.6**	**3.9**	**3.8**	**3.9**	**3.7**	**3.3**
CO_2	1.7	1.6	3.8	3.7	3.8	3.6	3.2
CH_4	+	+	+	+	+	+	+
N_2O	+	+	0.1	0.1	0.1	0.1	0.1
Commercial Aircraft[a]	**110.9**	**133.9**	**121.5**	**129.2**	**130.8**	**135.4**	**92.1**
CO_2	109.9	132.7	120.4	128.0	129.6	134.2	91.3
CH_4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N_2O	1.0	1.2	1.1	1.2	1.2	1.2	0.8
Other Aircraft[b]	**78.1**	**59.6**	**47.4**	**45.6**	**44.6**	**45.6**	**31.0**
CO_2	77.3	59.0	47.0	45.1	44.2	45.2	30.7
CH_4	0.1	0.1	+	+	+	+	+
N_2O	0.7	0.5	0.4	0.4	0.4	0.4	0.3
Ships and Boats[c]	**47.0**	**45.4**	**40.7**	**43.8**	**41.1**	**40.0**	**32.3**
CO_2	46.3	44.3	37.1	39.9	36.9	35.5	27.6
CH_4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N_2O	0.3	0.3	0.2	0.2	0.2	0.2	0.2
HFCs	0.0	0.5	2.9	3.3	3.6	3.9	4.2
Rail	**39.0**	**51.5**	**40.2**	**41.4**	**42.5**	**39.7**	**34.2**
CO_2	38.5	50.8	39.6	40.7	41.8	39.1	33.7
CH_4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	0.3	0.4	0.3	0.4	0.4	0.3	0.3
HFCs	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Emissions from Electric Power[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pipelines[e]	**36.0**	**32.4**	**39.2**	**41.3**	**49.9**	**57.9**	**57.1**
CO_2	36.0	32.4	39.2	41.3	49.9	57.9	57.1
Lubricants	**11.8**	**10.2**	**10.4**	**9.6**	**9.2**	**8.8**	**8.0**
CO_2	11.8	10.2	10.4	9.6	9.2	8.8	8.0
Total Transportation	**1,529.6**	**1,980.3**	**1,832.4**	**1,849.6**	**1,879.5**	**1,879.1**	**1,632.4**
International Bunker Fuels[f]	*54.8*	*44.7*	*35.0*	*34.6*	*32.5*	*26.4*	*22.7*
Ethanol CO_2[g]	*4.1*	*21.6*	*76.9*	*77.7*	*78.6*	*78.7*	*68.1*
Biodisel CO_2[g]	*0.0*	*0.9*	*19.6*	*18.7*	*17.9*	*17.1*	*17.7*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Consists of emissions from jet fuel consumed by domestic operations of commercial aircraft (no bunkers).

[b] Consists of emissions from jet fuel and aviation gasoline consumption by general aviation and military aircraft.

[c] Fluctuations in emission estimates are associated with fluctuations in reported fuel consumption and may reflect issues with data sources.

[d] Other emissions from electric power are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electric power plants), electrical transmission and distribution, and a portion of Other Process Uses of Carbonates (from pollution control equipment installed in electric power plants).

[e] CO_2 estimates reflect natural gas used to power pipelines, but not electricity. While the operation of pipelines produces CH_4 and N_2O, these emissions are not directly attributed to pipelines in the Inventory.

[f] Emissions from International Bunker Fuels include emissions from both civilian and military activities; these emissions are not included in the transportation totals.

[g] Ethanol and biodiesel CO_2 estimates are presented for informational purposes only. See Section 3.11 and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

Notes: Passenger cars and light-duty trucks include vehicles typically used for personal travel and less than 8,500 lbs; medium- and heavy-duty trucks include vehicles larger than 8,500 lbs. HFC emissions primarily reflect HFC-134a. Totals may not sum due to independent rounding.

Residential

The residential end-use sector, with electricity-related emissions distributed, accounts for 15.4 percent of U.S. greenhouse gas emissions in 2020 and similarly, is heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Emissions from the residential sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in housing and building attributes (e.g., larger sizes and improved insulation). A shift toward energy-efficient products and more stringent energy efficiency standards for household equipment has also contributed to recent trends in energy demand in households (EIA 2018).

Commercial

The commercial end-use sector, with electricity-related emissions distributed, accounts for 15.4 percent of U.S. greenhouse gas emissions in 2020 and is heavily reliant on electricity for meeting energy needs, with electricity use for lighting, heating, air conditioning, and operating appliances. The remaining emissions were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Energy-related emissions from the commercial sector have generally been increasing since 1990, and annual variations are often correlated with short-term fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Decreases in energy-related emissions in the commercial sector in recent years can be largely attributed to an overall reduction in energy use driven by a reduction in heating degree days and increases in energy efficiency.

Municipal landfills and wastewater treatment are included in the commercial sector, with landfill emissions decreasing since 1990 and wastewater treatment emissions decreasing slightly.

Agriculture

The agriculture end-use sector accounts for 11.2 percent of U.S. greenhouse gas emissions in 2020 when electricity-related emissions are distributed, and includes a variety of processes, including enteric fermentation in domestic livestock, livestock manure management, and agricultural soil management. In 2020, agricultural soil management was the largest source of N_2O emissions, and enteric fermentation was the largest source of CH_4 emissions in the United States. This sector also includes small amounts of CO_2 emissions from fossil fuel combustion by motorized farm equipment such as tractors.

Box 2-2: Trends in Various U.S. Greenhouse Gas Emissions-Related Data

Total greenhouse gas emissions can be compared to other economic and social indices to highlight changes over time. These comparisons include: (1) emissions per unit of aggregate energy use, because energy-related activities are the largest sources of emissions; (2) emissions per unit of fossil fuel consumption, because almost all energy-related emissions involve the combustion of fossil fuels; (3) emissions per unit of total gross domestic product as a measure of national economic activity; and (4) emissions per capita.

Table 2-14 provides data on various statistics related to U.S. greenhouse gas emissions normalized to 1990 as a baseline year. These values represent the relative change in each statistic since 1990. Greenhouse gas emissions in the United States have decreased at an average annual rate of 0.2 percent since 1990, although changes from year to year have been significantly larger. This growth rate is slightly slower than that for total energy use, overall gross domestic product (GDP) and national population (see Table 2-14 and Figure 2-15). The direction of these trends started to change after 2005, when greenhouse gas emissions, total energy use and associated fossil fuel consumption began to peak. Greenhouse gas emissions in the United States have decreased at an average annual rate of 1.4 percent since 2005. Fossil fuel consumption has also decreased at a slower rate than emissions since 2005, while total energy use, GDP, and national population, generally continued to increase, noting 2020 was impacted by the COVID-19 pandemic.

Table 2-14: Recent Trends in Various U.S. Data (Index 1990 = 100)

Variable	1990	2005	2016	2017	2018	2019	2020	Avg. Annual Change Since 1990[a]	Avg. Annual Change Since 2005[a]
Greenhouse Gas Emissions[b]	100	115	101	101	104	102	93	-0.2%	-1.4%
Energy Use[c]	100	119	116	116	120	119	109	0.3%	-0.5%
GDP[d]	100	159	189	193	199	203	196	2.3%	1.4%
Population[e]	100	118	128	129	129	131	132	0.9%	0.8%

[a] Average annual growth rate.

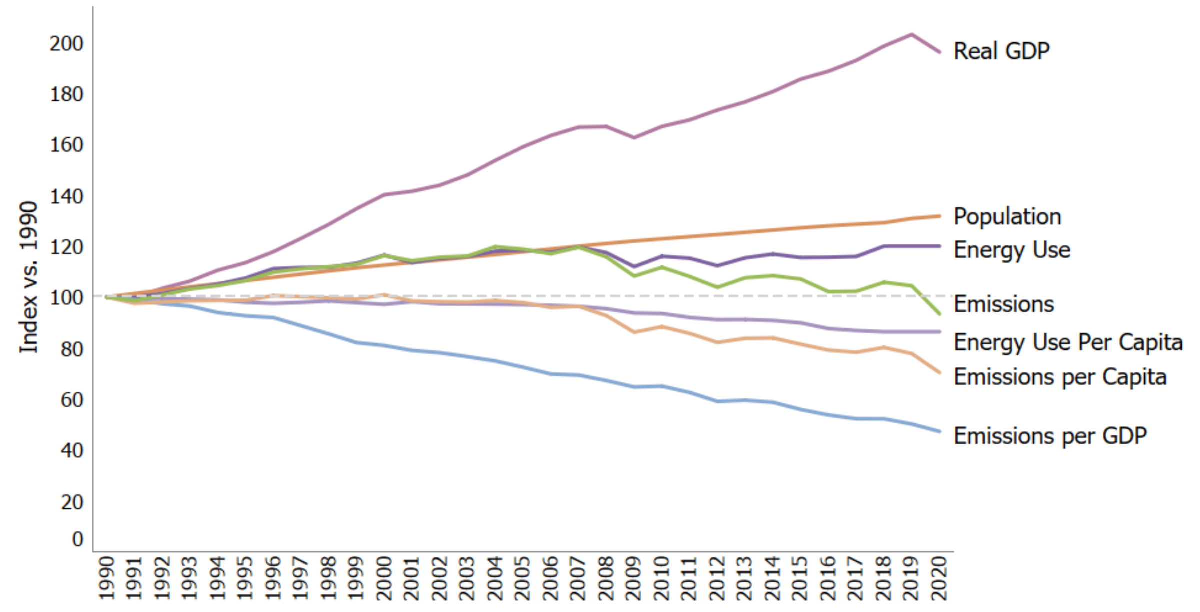
[b] GWP-weighted values.

[c] Energy-content-weighted values (EIA 2022).

[d] GDP in chained 2009 dollars (BEA 2021).

[e] U.S. Census Bureau (2021).

Figure 2-15: U.S. Greenhouse Gas Emissions Per Capita and Per Dollar of Gross Domestic Product



Source: BEA (2021), U.S. Census Bureau (2021), and emission estimates in this report.

2.3 Precursor Greenhouse Gas Emissions (CO, NO_x, NMVOCs, and SO_2)

The reporting requirements of the UNFCCC[11] request that information be provided on emissions of compounds that are precursors to greenhouse gases, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse

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[11] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

gases, but can indirectly impact Earth's radiative balance, by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Carbon monoxide is produced when carbon-containing fuels are combusted incompletely in energy, transportation, and industrial processes, and is also emitted from practices such as agricultural burning and waste disposal and treatment. Anthropogenic sources of nitrogen oxides (i.e., NO and NO_2) are primarily fossil fuel combustion (for energy, transportation, industrial process) and agricultural burning. Anthropogenic sources of NMVOCs, which include hundreds of organic compounds that participate in atmospheric chemical reactions (i.e., propane, butane, xylene, toluene, ethane, and many others)—are emitted primarily from transportation, industrial processes, oil and natural gas production, waste practices, agricultural burning, and non-industrial consumption of organic solvents. In the United States, SO_2 is primarily emitted from coal combustion for electric power generation and the metals industry.

As noted above and summarized in Chapter 6 of IPCC (2021), these compounds can have important indirect effects of Earth's radiative balance. For example, reactions between NMVOCs and NO_x in the presence of sunlight lead to tropospheric ozone formation, a greenhouse gas. Concentrations of NMVOCs, NO_x, and CO can also impact the abundance and lifetime of primary greenhouse gases. This largely occurs by altering the atmospheric concentrations of the hydroxyl radical (OH), which is the main sink for atmospheric CH_4. For example, NO_x emissions can lead to increases in O_3 concentrations and subsequent OH production, which will increase the amount of OH molecules that are available to destroy CH_4. In contrast, NMVOCs and CO can both react directly with OH, leading to lower OH concentrations, a longer atmospheric lifetime of CH_4, and a decrease in CO_2 production (i.e., $CO+OH \rightarrow CO_2$). Changes in atmospheric CH_4 can also feedback on background concentrations of tropospheric O_3. Other indirect impacts include the formation of sulfate and nitrate aerosol from emissions of NO_x and SO_2, both of which have a net negative impact on radiative forcing.

Since 1970, the United States has published triennial estimates of emissions of CO, NO_x, NMVOCs, and SO_2 (EPA 2021b), which are regulated under the Clean Air Act. Emissions of each of these precursor greenhouse gases has decreased significantly since 1990 as a result of implementation of Clean Air Act programs, as well as technological improvements.[12] Precursor emission estimates for this report for 1990 through 2020 were obtained from data published on EPA's National Emissions Inventory (NEI) Air Pollutants Emissions Trends Data website (EPA 2021b). For Table 2-15, NEI-reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Tier 1/Tier 2 source categories to those more closely aligned with IPCC categories, based on EPA (2022) and detailed in Annex 6. Table 2-15 shows that fuel combustion accounts for the majority of emissions of these precursors. Industrial processes—such as the manufacture of chemical and allied products, metals processing, and industrial uses of solvents—are also significant sources of CO, NO_x, and NMVOCs. Precursor emissions from Agriculture and LULUCF categories are estimated separately and therefore are not taken from EPA (2021b); see Sections 5.7, 6.2, and 6.6.

Table 2-15: Emissions of NO_x, CO, NMVOCs, and SO_2 (kt)

Gas/Activity	1990	2005	2016	2017	2018	2019	2020
NO_x	**21,764**	**17,333**	**8,792**	**8,483**	**8,008**	**7,425**	**7,128**
Energy	21,106	16,602	8,268	7,883	7,456	6,962	6,471
IPPU	592	572	402	397	397	397	397
LULUCF	52	142	107	188	139	50	244
Agriculture	13	15	14	14	14	14	14
Waste	+	2	1	1	1	1	1
CO	**132,759**	**74,553**	**39,981**	**43,688**	**39,531**	**34,170**	**43,799**
Energy	125,640	64,985	34,461	33,401	32,392	31,384	30,376
LULUCF	2,673	7,642	4,099	8,936	5,789	1,436	12,074
IPPU	4,129	1,557	1,075	1,007	1,007	1,007	1,007
Agriculture	315	363	340	339	338	337	336
Waste	1	7	6	5	5	5	5

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[12] More information is available online at: https://www.epa.gov/clean-air-act-overview/progress-cleaning-air-and-improving-peoples-health and https://gispub.epa.gov/neireport/2017/.

NMVOCs	**20,923**	**13,309**	**9,855**	**9,483**	**9,310**	**9,136**	**8,963**
Energy	12,612	7,345	6,022	5,664	5,491	5,318	5,145
IPPU	7,638	5,849	3,776	3,767	3,767	3,767	3,767
Waste	673	114	57	52	52	52	52
Agriculture	NA	NA	NA	NA	NA	NA	NA
LULUCF	NA	NA	NA	NA	NA	NA	NA
SO_2	**20,935**	**13,196**	**2,906**	**2,303**	**2,211**	**1,943**	**1,780**
Energy	19,628	12,364	2,439	1,794	1,701	1,433	1,270
IPPU	1,307	831	466	509	509	509	509
Waste	+	1	1	1	1	1	1
Agriculture	NA	NA	NA	NA	NA	NA	NA
LULUCF	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA (Not Available)

Note: Totals may not sum due to independent rounding.

Source: (EPA 2021b) except for estimates from Forest Fires, Grassland Fires, and Field Burning of Agricultural Residues. Emission categories from EPA (2021b) are aggregated into IPCC categories following as shown in Table ES-3.

3. Energy

Energy-related activities were the primary sources of U.S. anthropogenic greenhouse gas emissions, accounting for 81.2 percent of total greenhouse gas emissions on a carbon dioxide (CO_2) equivalent basis in 2020.[1] This included 96.4, 41.4, and 9.6 percent of the nation's CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, respectively. Energy-related CO_2 emissions alone constituted 76.0 percent of U.S. greenhouse gas emissions from all sources on a CO_2-equivalent basis, while the non-CO_2 emissions from energy-related activities represented a much smaller portion of total national emissions (5.2 percent collectively).

Emissions from fossil fuel combustion comprise the vast majority of energy-related emissions, with CO_2 being the primary gas emitted (see Figure 3-1 and Figure 3-2). Globally, approximately 31,500 million metric tons (MMT) of CO_2 were added to the atmosphere through the combustion of fossil fuels in 2020, of which the United States accounted for approximately 14 percent.[2] Due to their relative importance over time (see Figure 3-2), fossil fuel combustion-related CO_2 emissions are considered in more detail than other energy-related emissions in this report (see Figure 3-3).

Fossil fuel combustion also emits CH_4 and N_2O. Stationary combustion of fossil fuels was the third largest source of N_2O emissions in the United States and mobile fossil fuel combustion was the fifth largest source. Energy-related activities other than fuel combustion, such as the production, transmission, storage, and distribution of fossil fuels, also emit greenhouse gases. These emissions consist primarily of fugitive CH_4 emissions from natural gas systems, coal mining, and petroleum systems.

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[1] Estimates are presented in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.), which weight each gas by its global warming potential, or GWP, value. See section on global warming potentials in the Executive Summary.

[2] Global CO_2 emissions from fossil fuel combustion were taken from International Energy Agency *Global energy-related CO_2 emissions, 1990-2020 – Charts* Available at: https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-1990-2020 (IEA 2021).

Figure 3-1: 2020 Energy Sector Greenhouse Gas Sources

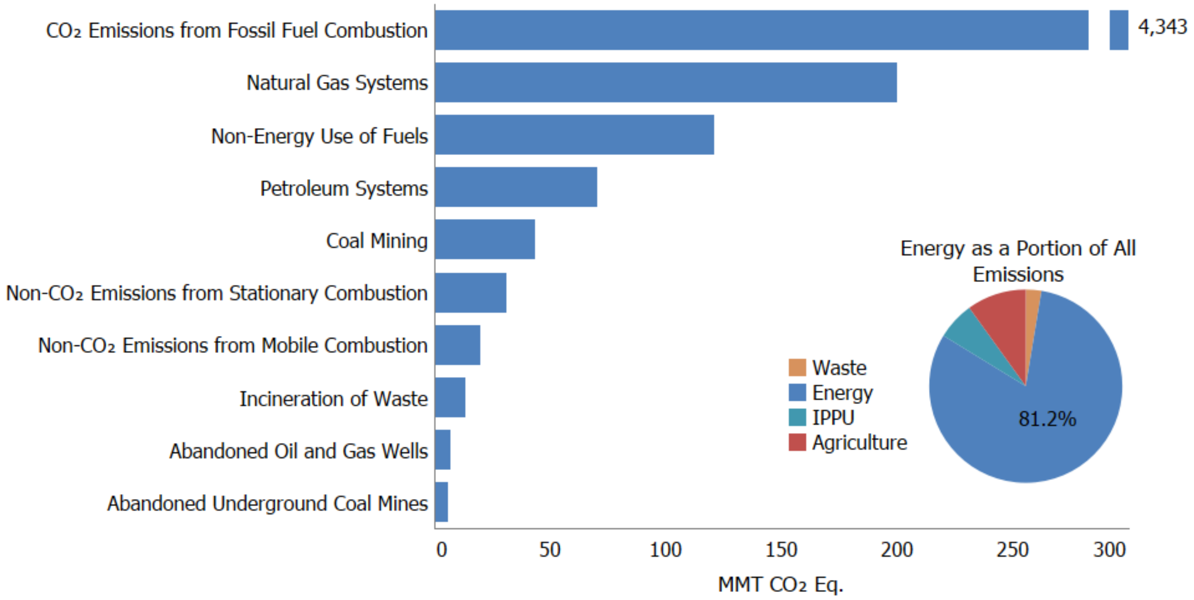


Figure 3-2: Trends in Energy Sector Greenhouse Gas Sources

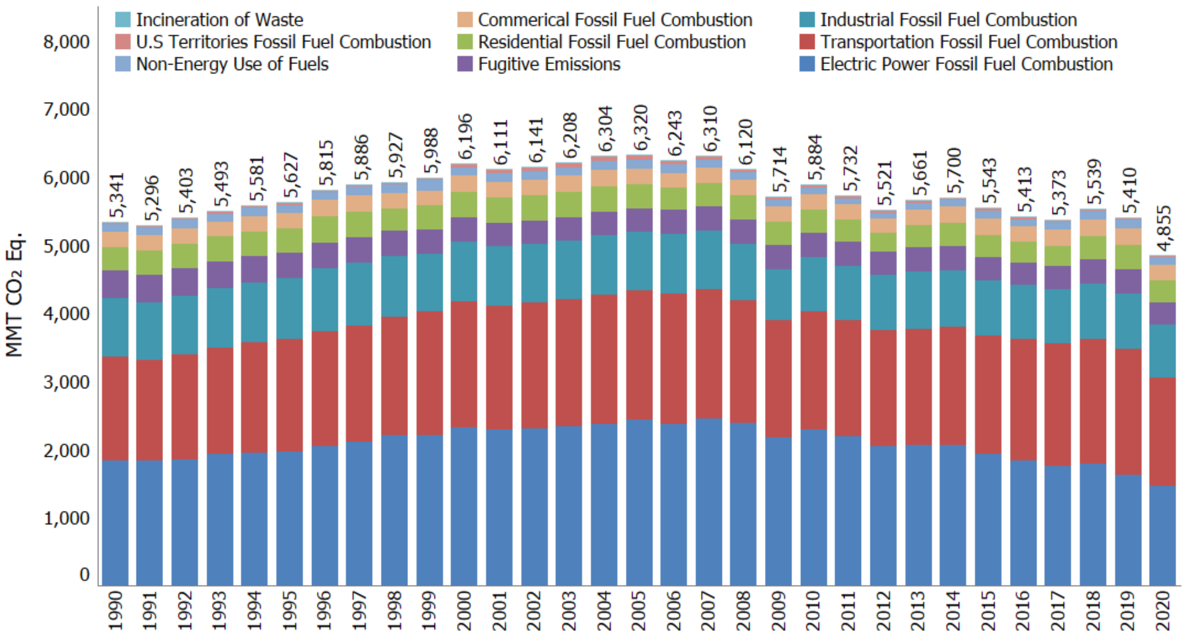
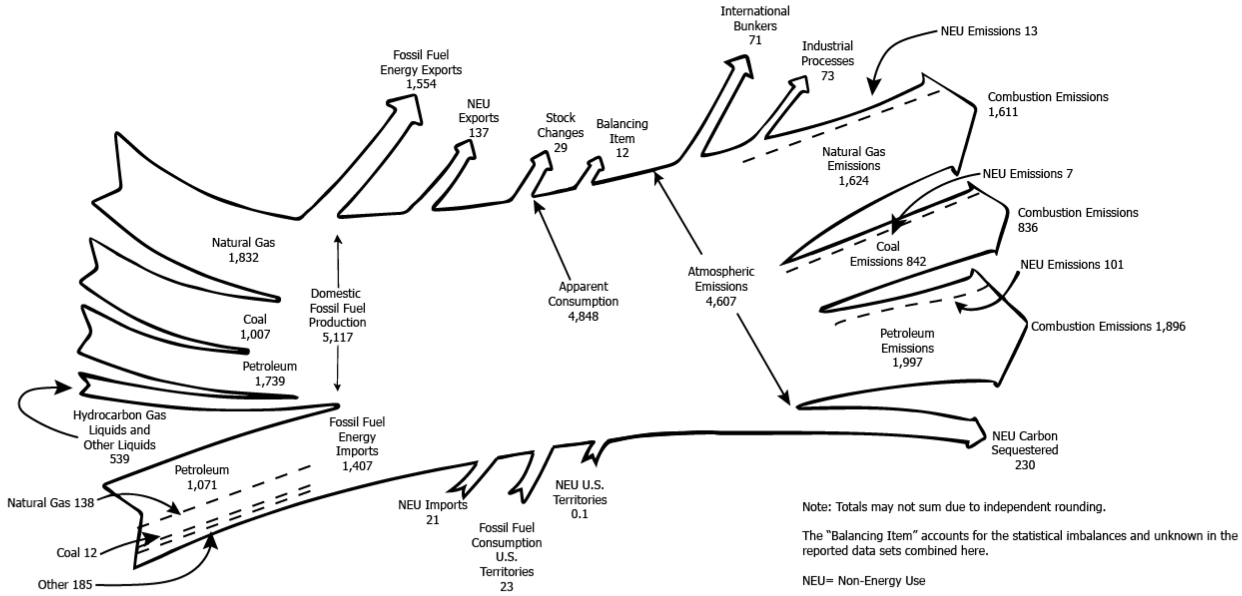


Figure 3-3: 2020 U.S. Fossil Carbon Flows



Note: Totals may not sum due to independent rounding.

The "Balancing Item" accounts for the statistical imbalances and unknown in the reported data sets combined here.

NEU= Non-Energy Use

Table 3-1 summarizes emissions from the Energy sector in units of MMT CO_2 Eq., while unweighted gas emissions in kilotons (kt) are provided in Table 3-2. Overall, emissions due to energy-related activities were 4,854.7 MMT CO_2 Eq. in 2020,[3] a decrease of 9.1 percent since 1990 and a decrease of 10.3 percent since 2019. The decrease in 2020 emissions was due primarily to the coronavirus (COVID-19) pandemic reducing overall demand for fossil fuels across all sectors but it also reflects a continued shift from coal to natural gas and renewables in the electric power sector.

Table 3-1: CO_2, CH_4, and N_2O Emissions from Energy (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**4,902.4**	**5,935.4**	**5,078.0**	**5,038.3**	**5,204.3**	**5,080.4**	**4,544.5**
Fossil Fuel Combustion	4,731.2	5,752.0	4,909.6	4,853.3	4,989.3	4,852.3	4,342.7
Transportation	*1,468.9*	*1,858.6*	*1,757.6*	*1,780.0*	*1,812.8*	*1,813.8*	*1,572.0*
Electricity Generation	*1,820.0*	*2,400.1*	*1,808.9*	*1,732.0*	*1,752.9*	*1,606.1*	*1,439.0*
Industrial	*853.7*	*851.5*	*792.7*	*790.4*	*814.1*	*816.1*	*766.3*
Residential	*338.6*	*358.9*	*292.8*	*293.4*	*338.2*	*341.4*	*315.8*
Commercial	*228.3*	*227.1*	*231.5*	*232.0*	*245.8*	*250.7*	*226.8*
U.S. Territories	*21.7*	*55.9*	*26.0*	*25.5*	*25.5*	*24.3*	*22.7*
Non-Energy Use of Fuels	112.2	128.9	99.5	112.6	128.9	126.8	121.0
Natural Gas Systems	31.9	24.9	29.8	31.1	32.4	38.7	35.4
Petroleum Systems	9.6	12.0	21.9	25.0	37.3	46.7	30.2
Incineration of Waste	12.9	13.3	14.4	13.2	13.3	12.9	13.1
Coal Mining	4.6	4.2	2.8	3.1	3.1	3.0	2.2
Abandoned Oil and Gas Wells	+	+	+	+	+	+	+
Biomass-Wood[a]	*215.2*	*206.9*	*216.0*	*211.9*	*220.0*	*217.6*	*202.1*
Biofuels-Ethanol[a]	*4.2*	*22.9*	*81.2*	*82.1*	*81.9*	*82.6*	*71.8*
International Bunker Fuels[b]	*103.6*	*113.3*	*116.7*	*120.2*	*122.2*	*116.1*	*69.6*
Biofuels-Biodiesel[a]	*0.0*	*0.9*	*19.6*	*18.7*	*17.9*	*17.1*	*17.7*
CH_4	**368.6**	**308.3**	**283.5**	**285.4**	**287.3**	**284.0**	**269.1**

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[3] Following the current reporting requirements under the UNFCCC, this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

Natural Gas Systems	195.5	177.5	165.2	166.6	171.8	172.1	164.9
Coal Mining	96.5	64.1	53.8	54.8	52.7	47.4	41.2
Petroleum Systems	47.8	41.4	40.4	40.5	38.6	40.4	40.2
Stationary Combustion	8.6	7.8	7.9	7.7	8.6	8.8	7.9
Abandoned Oil and Gas Wells	6.5	6.8	6.9	6.9	6.9	7.0	6.9
Abandoned Underground Coal Mines	7.2	6.6	6.7	6.4	6.2	5.9	5.8
Mobile Combustion	6.5	4.0	2.6	2.6	2.5	2.5	2.2
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.2*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
N_2O	**70.1**	**76.1**	**51.5**	**49.0**	**47.9**	**45.3**	**41.1**
Stationary Combustion	25.1	34.4	30.0	28.4	28.2	24.9	23.2
Mobile Combustion	44.6	41.4	21.1	20.1	19.2	20.0	17.4
Incineration of Waste	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*0.9*	*1.0*	*1.0*	*1.1*	*1.1*	*1.0*	*0.6*
Total	**5,341.1**	**6,319.8**	**5,413.1**	**5,372.7**	**5,539.4**	**5,409.8**	**4,854.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions from Wood Biomass and Biofuel Consumption are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Table 3-2: CO_2, CH_4, and N_2O Emissions from Energy (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**4,902,396**	**5,935,361**	**5,078,027**	**5,038,320**	**5,204,305**	**5,080,437**	**4,544,464**
Fossil Fuel Combustion	4,731,178	5,752,043	4,909,609	4,853,299	4,989,308	4,852,330	4,342,659
Non-Energy Use of Fuels	112,175	128,920	99,505	112,616	128,871	126,776	120,987
Natural Gas Systems	31,894	24,945	29,780	31,145	32,407	38,740	35,353
Petroleum Systems	9,600	11,994	21,922	25,027	37,306	46,686	30,156
Incineration of Waste	12,937	13,283	14,356	13,161	13,339	12,948	13,133
Coal Mining	4,606	4,170	2,848	3,067	3,067	2,951	2,169
Abandoned Oil and Gas Wells	6	7	7	7	7	7	7
Biomass-Wood[a]	*215,186*	*206,901*	*215,955*	*211,925*	*219,951*	*217,574*	*202,088*
Biofuels-Ethanol[a]	*4,227*	*22,943*	*81,250*	*82,088*	*81,917*	*82,578*	*71,847*
International Bunker Fuels[b]	*103,634*	*113,328*	*116,682*	*120,192*	*122,179*	*116,132*	*69,638*
Biofuels-Biodiesel[a]	*0*	*856*	*19,648*	*18,705*	*17,936*	*17,080*	*17,678*
CH_4	**14,744**	**12,331**	**11,342**	**11,417**	**11,492**	**11,360**	**10,766**
Natural Gas Systems	7,821	7,100	6,609	6,662	6,871	6,885	6,596
Coal Mining	3,860	2,565	2,154	2,191	2,109	1,895	1,648
Petroleum Systems	1,912	1,655	1,616	1,621	1,544	1,615	1,609
Stationary Combustion	344	313	315	307	344	351	317

Abandoned Oil and Gas Wells	261	273	275	276	277	279	276
Abandoned Underground Coal Mines	288	264	268	257	247	237	231
Mobile Combustion	259	161	105	102	99	99	88
Incineration of Waste	+	+	+	+	+	+	+
International Bunker Fuels[b]	*7*	*5*	*4*	*4*	*4*	*4*	*3*
N_2O	**235**	**255**	**173**	**164**	**161**	**152**	**138**
Stationary Combustion	84	115	101	95	95	84	78
Mobile Combustion	150	139	71	68	64	67	58
Incineration of Waste	2	1	1	1	1	1	1
Petroleum Systems	+	+	+	+	+	+	+
Natural Gas Systems	+	+	+	+	+	+	+
International Bunker Fuels[b]	*3*	*3*	*3*	*4*	*4*	*3*	*2*

+ Does not exceed 0.5 kt.

[a] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

[b] Emissions from International Bunker Fuels are not included in totals. These values are presented for informational purposes only, in line with the *2006 IPCC Guidelines* and UNFCCC reporting obligations.

Note: Totals may not sum due to independent rounding.

Emissions estimates reported in the Energy chapter from fossil fuel combustion and fugitive sources include those from all 50 states, including Hawaii and Alaska, and the District of Columbia. Emissions are also included from U.S. Territories to the extent they are known to occur (e.g., coal mining does not occur in U.S. Territories). For some sources there is a lack of detailed information on U.S. Territories including some non-CO_2 emissions from biomass combustion. As part of continuous improvement efforts, EPA reviews this on an ongoing basis to ensure emission sources are included across all geographic areas including U.S. Territories if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this Inventory.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate. Key updates in this year's Inventory include updates to the Incineration of Waste methodology (e.g., new waste tonnage estimates data sources to replace proxied data, new GHGRP carbon emission factor, and new MSW incineration activity data), updated emission factors for CH_4 and N_2O from newer non-road gasoline and diesel vehicles for emissions from Mobile Combustion, revisions to the Natural Gas Systems methodology (e.g., inclusion of post-meter emissions, adding well blowout emissions, and changes to methane reduction data processing), changes to the Abandoned Oil and Gas Wells methodology to improve estimates of plugged wells, changes to the Non-Energy Use of Fossil Fuel methodology (e.g., updated energy consumption statistics, updated polyester fiber and acetic acid production data, updated import and export data, and updated shipment data from the U.S census Bureau). The combined impact of these recalculations averaged 19.3 MMT CO_2 Eq. (+0.3 percent) per year across the time series. For more information on specific methodological updates, please see the Recalculations Discussion section for each category in this chapter.

Box 3-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to EPA's Greenhouse Gas Reporting Program

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the Energy chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from energy-related activities.

Energy Data from EPA's Greenhouse Gas Reporting Program

EPA's Greenhouse Gas Reporting Program (GHGRP)[4] dataset and the data presented in this Inventory are complementary. The Inventory was used to guide the development of the GHGRP, particularly in terms of scope and coverage of both sources and gases. The GHGRP dataset continues to be an important resource for the Inventory, providing not only annual emissions information, but also other annual information, such as activity data and emission factors that can improve and refine national emission estimates and trends over time. GHGRP data also allow EPA to disaggregate national inventory estimates in new ways that can highlight differences across regions and sub-categories of emissions, along with enhancing application of QA/QC procedures and assessment of uncertainties.

EPA uses annual GHGRP data in a number of Energy sector categories to improve the national estimates presented in this Inventory consistent with IPCC guidelines (see Box 3-3 of this chapter, and sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.6 Natural Gas Systems).[5] Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods. Under EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards. It should be noted that the definitions and provisions for reporting fuel types in EPA's GHGRP may differ from those used in the Inventory in meeting the UNFCCC reporting guidelines. In line with the UNFCCC reporting guidelines, the Inventory report is a comprehensive accounting of all emissions from fuel types identified in the IPCC guidelines and provides a separate reporting of emissions from biomass.

In addition to using GHGRP data to estimate emissions (Sections 3.3 Incineration of Waste, 3.4 Coal Mining, 3.6 Petroleum Systems, and 3.6 Natural Gas Systems), EPA also uses the GHGRP fuel consumption activity data in the Energy sector to disaggregate industrial end-use sector emissions in the category of CO_2 Emissions from Fossil Fuel Combustion, for use in reporting emissions in Common Reporting Format (CRF) tables (See Box 3-3). The industrial end-use sector activity data collected for the Inventory (EIA 2022) represent aggregated data for the industrial end-use sector. EPA's GHGRP collects industrial fuel consumption activity data by individual categories within the industrial end-use sector. Therefore, GHGRP data are used to provide a more detailed breakout of total emissions in the industrial end-use sector within that source category.

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[4] On October 30, 2009, the U.S. Environmental Protection Agency (EPA) published a rule requiring annual reporting of greenhouse gas data from large greenhouse gas emission sources in the United States. Implementation of the rule, codified at 40 CFR Part 98, is referred to as EPA's Greenhouse Gas Reporting Program (GHGRP).

[5] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

As indicated in the respective Planned Improvements sections for source categories in this chapter, EPA continues to examine the uses of facility-level GHGRP data to improve the national estimates presented in this Inventory. See Annex 9 for more information on use of EPA's GHGRP in the Inventory.

3.1 Fossil Fuel Combustion (CRF Source Category 1A)

Emissions from the combustion of fossil fuels for energy include the greenhouse gases CO_2, CH_4, and N_2O. Given that CO_2 is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total emissions, CO_2 emissions from fossil fuel combustion are discussed at the beginning of this section. An overview of CH_4 and N_2O emissions from the combustion of fuels in stationary sources is then presented, followed by fossil fuel combustion emissions for all three gases by sector: electric power, industrial, residential, commercial, U.S. Territories, and transportation.

Methodologies for estimating CO_2 emissions from fossil fuel combustion differ from the estimation of CH_4 and N_2O emissions from stationary combustion and mobile combustion. Thus, three separate descriptions of methodologies, uncertainties, recalculations, and planned improvements are provided at the end of this section. Total CO_2, CH_4, and N_2O emissions from fossil fuel combustion are presented in Table 3-3 and Table 3-4.

Table 3-3: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	4,731.2	5,752.0	4,909.6	4,853.3	4,989.3	4,852.3	4,342.7
CH_4	15.1	11.9	10.5	10.2	11.1	11.2	10.1
N_2O	69.7	75.7	51.1	48.6	47.4	44.9	40.6
Total	**4,815.9**	**5,839.6**	**4,971.2**	**4,912.1**	**5,047.8**	**4,908.4**	**4,393.4**

Note: Totals may not sum due to independent rounding.

Table 3-4: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	4,731,178	5,752,043	4,909,609	4,853,299	4,989,308	4,852,330	4,342,659
CH_4	603	474	420	409	443	450	406
N_2O	234	254	171	163	159	151	136

CO_2 from Fossil Fuel Combustion

Carbon dioxide is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. total greenhouse gas emissions. Carbon dioxide emissions from fossil fuel combustion are presented in Table 3-5. In 2020, CO_2 emissions from fossil fuel combustion decreased by 10.5 percent relative to the previous year (as shown in Table 3-6). The decrease in CO_2 emissions from fossil fuel consumption was a result of a 9.2 percent decrease in fossil fuel energy use. This decrease in fossil fuel consumption was due primarily to the COVID-19 pandemic but also reflects a continued shift from coal to natural gas and renewables. Carbon dioxide emissions from both natural gas and coal consumption decreased in 2020. CO_2 emissions from natural gas decreased by 38.0 MMT CO_2 Eq., a 2.3 percent decrease from 2019. CO_2 emissions from coal consumption decreased by 192.6 MMT CO_2 Eq., an 18.7 percent decrease from 2019. The decrease in natural gas consumption and emissions in 2020 is observed across all sectors except the Electric Power sector. This increase in the Electric Power sector is primarily driven by a continued shift away from coal consumption to natural gas. In 2020, CO_2 emissions from fossil fuel combustion were 4,342.7 MMT CO_2 Eq., or 8.2 percent below emissions in 1990 (see Table 3-5).[6]

Table 3-5: CO_2 Emissions from Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq.)

Fuel/Sector	1990	2005	2016	2017	2018	2019	2020
Coal	**1,719.8**	**2,113.7**	**1,310.7**	**1,270.0**	**1,211.6**	**1,028.2**	**835.6**
Residential	3.0	0.8	0.0	0.0	0.0	0.0	0.0
Commercial	12.0	9.3	2.3	2.0	1.8	1.6	1.4
Industrial	157.8	117.8	63.2	58.7	54.4	49.5	43.0
Transportation	NO	NO	NO	NO	NO	NO	NO
Electric Power	1,546.5	1,982.8	1,242.0	1,207.1	1,152.9	973.5	788.2
U.S. Territories	0.5	3.0	3.3	2.3	2.6	3.6	3.1
Natural Gas	**1,000.0**	**1,167.0**	**1,461.3**	**1,434.6**	**1,592.0**	**1,648.8**	**1,610.7**
Residential	237.8	262.2	238.4	241.5	273.8	275.5	256.4
Commercial	142.0	162.9	170.5	173.2	192.5	192.9	173.9
Industrial	408.8	388.6	463.9	469.5	494.0	501.6	485.5
Transportation	36.0	33.1	40.1	42.3	50.9	58.9	58.1
Electric Power	175.4	318.9	545.0	505.6	577.4	616.0	634.3
U.S. Territories	NO	1.3	3.4	2.5	3.3	3.8	2.6
Petroleum	**2,010.9**	**2,470.9**	**2,137.2**	**2,148.3**	**2,185.3**	**2,175.0**	**1,895.9**
Residential	97.8	95.9	54.4	51.9	64.4	65.9	59.5
Commercial	74.3	54.9	58.7	56.8	51.5	56.2	51.6
Industrial	287.1	345.0	265.7	262.2	265.7	265.0	237.8
Transportation	1,432.9	1,825.5	1,717.6	1,737.7	1,761.8	1,754.8	1,514.0
Electric Power	97.5	98.0	21.5	18.9	22.2	16.2	16.2
U.S. Territories	21.2	51.6	19.4	20.6	19.6	16.9	16.9
Geothermal[a]	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Electric Power	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Total	**4,731.2**	**5,752.0**	**4,909.6**	**4,853.3**	**4,989.3**	**4,852.3**	**4,342.7**

NO (Not Occurring)

[a] Although not technically a fossil fuel, geothermal energy-related CO_2 emissions are included for reporting purposes. The source of CO_2 is non-condensable gases in subterranean heated water.

Note: Totals may not sum due to independent rounding.

Trends in CO_2 emissions from fossil fuel combustion are influenced by many long-term and short-term factors. On a year-to-year basis, the overall demand for fossil fuels in the United States and other countries generally fluctuates in response to changes in general economic conditions, energy prices, weather, and the availability of non-fossil alternatives. For example, in a year with increased consumption of goods and services, low fuel prices, severe summer and winter weather conditions, nuclear plant closures, and lower precipitation feeding hydroelectric dams, there would likely be proportionally greater fossil fuel consumption than a year with poor economic performance, high fuel prices, mild temperatures, and increased output from nuclear and hydroelectric plants. The 2019 to 2020 trends were particularly impacted by the COVID-19 pandemic which generally led to a reduction in demand for fossil fuels.

Longer-term changes in energy usage patterns, however, tend to be more a function of aggregate societal trends that affect the scale of energy use (e.g., population, number of cars, size of houses, and number of houses), the efficiency with which energy is used in equipment (e.g., cars, HVAC systems, power plants, steel mills, and light bulbs), and social planning and consumer behavior (e.g., walking, bicycling, or telecommuting to work instead of driving).

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[6] An additional discussion of fossil fuel emission trends is presented in the Trends in U.S. Greenhouse Gas Emissions chapter.

Carbon dioxide emissions also depend on the source of energy and its carbon (C) intensity. The amount of C in fuels varies significantly by fuel type. For example, coal contains the highest amount of C per unit of useful energy. Petroleum has roughly 75 percent of the C per unit of energy as coal, and natural gas has only about 55 percent.[7] Table 3-6 shows annual changes in emissions during the last five years for coal, petroleum, and natural gas in selected sectors.

Table 3-6: Annual Change in CO_2 Emissions and Total 2020 CO_2 Emissions from Fossil Fuel Combustion for Selected Fuels and Sectors (MMT CO_2 Eq. and Percent)

Sector	Fuel Type	2016 to 2017		2017 to 2018		2018 to 2019		2019 to 2020		Total 2020
Transportation	Petroleum	20.1	1.2%	24.1	1.4%	-7.0	-0.4%	-240.9	-13.7%	1,514.0
Electric Power	Coal	-34.9	-2.8%	-54.2	-4.5%	-179.3	-15.6%	-185.4	-19.0%	788.2
Electric Power	Natural Gas	-39.4	-7.2%	71.8	14.2%	38.6	6.7%	18.2	3.0%	634.3
Industrial	Natural Gas	5.6	1.2%	24.5	5.2%	7.7	1.6%	-16.1	-3.2%	485.5
Residential	Natural Gas	3.1	1.3%	32.3	13.4%	1.7	0.6%	-19.1	-6.9%	256.4
Commercial	Natural Gas	2.6	1.6%	19.3	11.2%	0.4	0.2%	-19.1	-9.9%	173.9
Transportation	**All Fuels[a]**	**22.3**	**1.3%**	**32.8**	**1.8%**	**1.0**	**0.1%**	**-241.7**	**-13.3%**	**1,572.0**
Electric Power	**All Fuels[a]**	**-76.8**	**-4.2%**	**20.9**	**1.2%**	**-146.8**	**-8.4%**	**-167.1**	**-10.4%**	**1,439.0**
Industrial	**All Fuels[a]**	**-2.3**	**-0.3%**	**23.7**	**3.0%**	**2.0**	**0.2%**	**-49.8**	**-6.1%**	**766.3**
Residential	**All Fuels[a]**	**0.6**	**0.2%**	**44.8**	**15.3%**	**3.2**	**0.9%**	**-25.6**	**-7.5%**	**315.8**
Commercial	**All Fuels[a]**	**0.5**	**0.2%**	**13.8**	**6.0%**	**4.9**	**2.0%**	**-23.9**	**-9.5%**	**226.8**
All Sectors[a]	**All Fuels[a]**	**-56.3**	**-1.1%**	**136.0**	**2.8%**	**-137.0**	**-2.7%**	**-509.7**	**-10.5%**	**4,342.7**

+ Does not exceed 0.05 percent.

[a] Includes sector and fuel combinations not shown in this table.

As shown in Table 3-6, recent trends in CO_2 emissions from fossil fuel combustion show a 1.1 percent decrease from 2016 to 2017, a 2.8 percent increase from 2017 to 2018, a 2.7 percent decrease from 2018 to 2019, and a 10.5 percent decrease from 2019 to 2020. These changes contributed to an overall 11.5 percent decrease in CO_2 emissions from fossil fuel combustion from 2016 to 2020.

Recent trends in CO_2 emissions from fossil fuel combustion are largely driven by the electric power sector, which until recently has accounted for the largest portion of these emissions. The types of fuels consumed to produce electricity have changed in recent years. Electric power sector consumption of natural gas primarily increased due to increased production capacity as natural gas-fired plants replaced coal-fired plants and increased electricity demand related to heating and cooling needs (EIA 2018; EIA 2021d). Total electric power generation from all fossil and non-fossil sources decreased by 1.0 percent from 2016 to 2017, increased by 3.6 percent from 2017 to 2018, decreased by 1.3 percent from 2018 to 2019 and decreased by 2.9 percent from 2019 to 2020. Carbon dioxide emissions decreased from 2019 to 2020 by 10.4 percent due to decreasing electric power generation from petroleum and coal outweighing increases in natural gas generation. Carbon dioxide emissions from coal consumption for electric power generation decreased by 36.5 percent since 2016, which can be largely attributed to a shift to the use of less-CO_2-intensive natural gas to generate electricity and a rapid increase in renewable energy capacity additions in the electric power sector in recent years.

The recent trends in CO_2 emissions from fossil fuel combustion also follow changes in heating degree days (see Box 3-2). Emissions from natural gas consumption in the residential and commercial sectors increased by 7.0 percent and 1.9 percent from 2016 to 2020, respectively. This trend can be partially attributed to a 1.0 percent increase in heating degree days from 2016 to 2020, which led to an increased demand for heating fuel and electricity for heat in these sectors. Industrial consumption of natural gas is dependent on market effects of supply and demand in addition to weather-related heating needs.

Petroleum use in the transportation sector is another major driver of emissions, representing the largest source of CO_2 emissions from fossil fuel combustion in 2020. Emissions from petroleum consumption for transportation have

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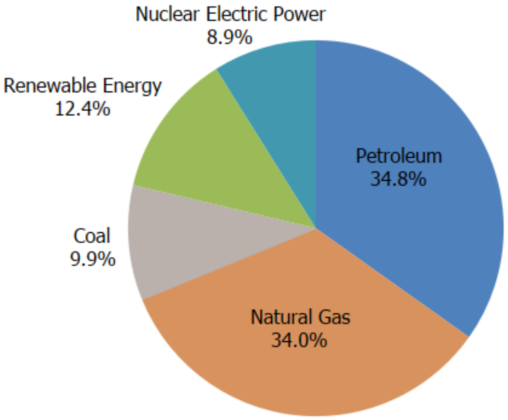
[7] Based on national aggregate carbon content of all coal, natural gas, and petroleum fuels combusted in the United States. See Annex 2.2 for more details on fuel carbon contents.

decreased by 11.9 percent since 2016 and are primarily attributed to a 8.5 percent decrease in VMT over the same time period. This decrease in VMT was largely due to the impacts of the COVID-19 pandemic which limited travel in 2020. Beginning with 2017, the transportation sector is the largest source of national CO_2 emissions–whereas in prior years, electric power was the largest source sector.

The 2019 to 2020 trends were largely driven by the COVID-19 pandemic which reduced economic activity and caused changes in energy demand and supply patterns across different sectors in 2020. Reduced economic and manufacturing activity resulted in lower energy use in the commercial and industrial sectors. More people working from home combined with warmer temperatures in 2020 compared to 2019 resulted in a mixed impact on energy use in the residential sector. People staying home in response to the COVID-19 pandemic combined with increased summer cooling demand resulted in an increase in residential sector electricity use while lowered residential space heating demand resulted in reduced natural gas use in the residential sector. Overall consumption of electricity in the United States decreased in 2020 and the trend of decreased coal use and increased use of natural gas and renewables continued. Reduced travel caused by the COVID-19 pandemic resulted in decreased energy use in the transportation sector in 2020 compared to 2019, including decreased road transportation but in particular decreased aviation travel.

In the United States, 78.8 percent of the energy used in 2020 was produced through the combustion of fossil fuels such as petroleum, natural gas, and coal (see Figure 3-4 and Figure 3-5). Specifically, petroleum supplied the largest share of domestic energy demands, accounting for 35 percent of total U.S. energy used in 2020. Natural gas and coal followed in order of fossil fuel energy demand importance, accounting for approximately 34 percent and 10 percent of total U.S. energy used, respectively. Petroleum was consumed primarily in the transportation end-use sector and the majority of coal was used in the electric power sector. Natural gas was broadly consumed in all end-use sectors except transportation (see Figure 3-6) (EIA 2021c). The remaining portion of energy used in 2020 was supplied by nuclear electric power (9 percent) and by a variety of renewable energy sources (12 percent), primarily wind energy, hydroelectric power, solar, geothermal and biomass (EIA 2021c).[8]

Figure 3-4: 2020 U.S. Energy Use by Energy Source



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[8] Renewable energy, as defined in EIA's energy statistics, includes the following energy sources: hydroelectric power, geothermal energy, biomass, solar energy, and wind energy.

Figure 3-5: Annual U.S. Energy Use

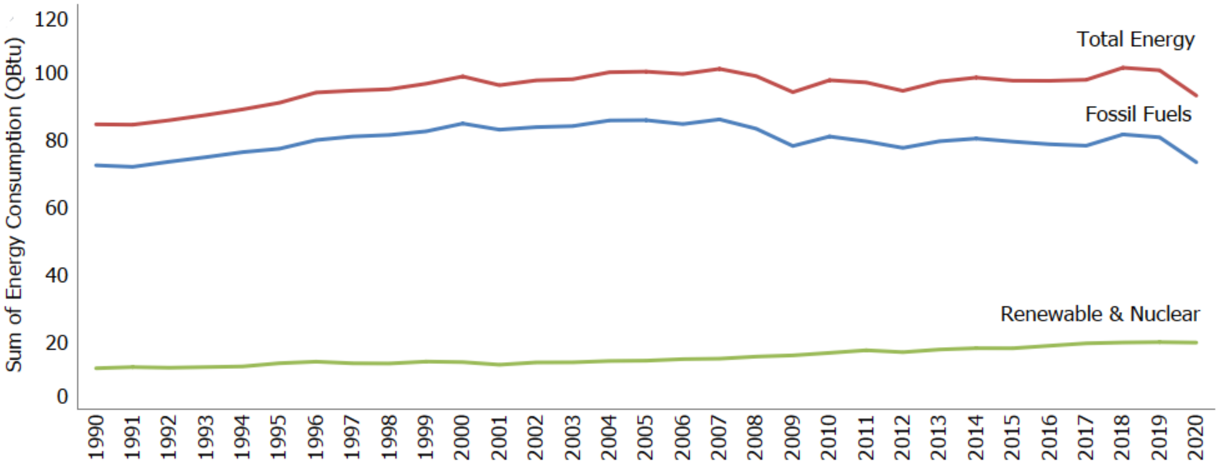
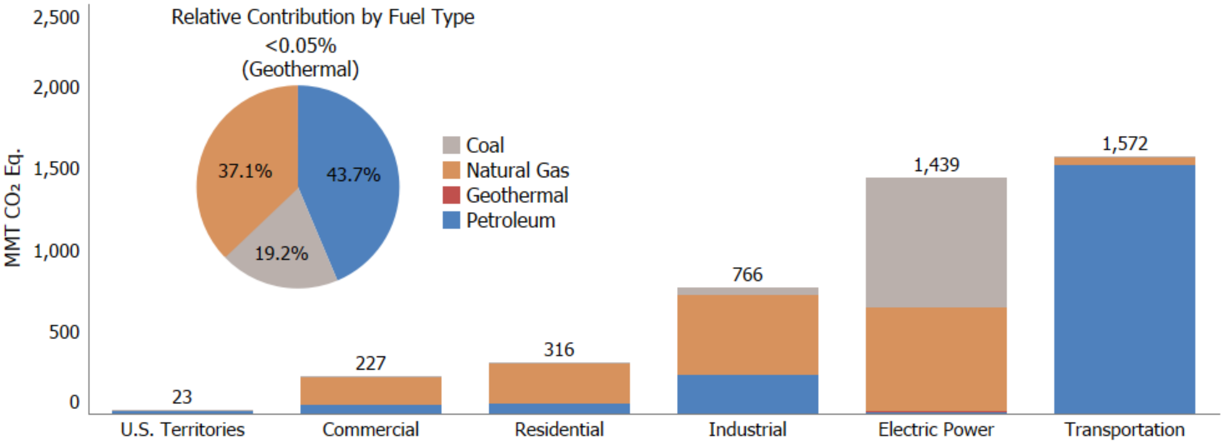


Figure 3-6: 2020 CO_2 Emissions from Fossil Fuel Combustion by Sector and Fuel Type



Fossil fuels are generally combusted for the purpose of producing energy for useful heat and work. During the combustion process, the C stored in the fuels is oxidized and emitted as CO_2 and smaller amounts of other gases, including CH_4, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs).[9] These other C-containing non-CO_2 gases are emitted as a byproduct of incomplete fuel combustion, but are, for the most part, eventually oxidized to CO_2 in the atmosphere. Therefore, as per IPCC guidelines it is assumed all of the C in fossil fuels used to produce energy is eventually converted to atmospheric CO_2.

Box 3-2: Weather and Non-Fossil Energy Effects on CO_2 Emissions from Fossil Fuel Combustion Trends

The United States in 2020 experienced a warmer winter overall compared to 2019, as heating degree days decreased 9.4 percent. Warmer winter conditions compared to 2019 impacted the amount of energy required for heating. In 2020 heating degree days in the United States were 9.8 percent below normal (see Figure 3-7). Cooling degree days increased by 1.5 percent compared to 2019, which increased demand for air conditioning in the residential and commercial sector. Hotter summer conditions compared to 2019 impacted the amount of

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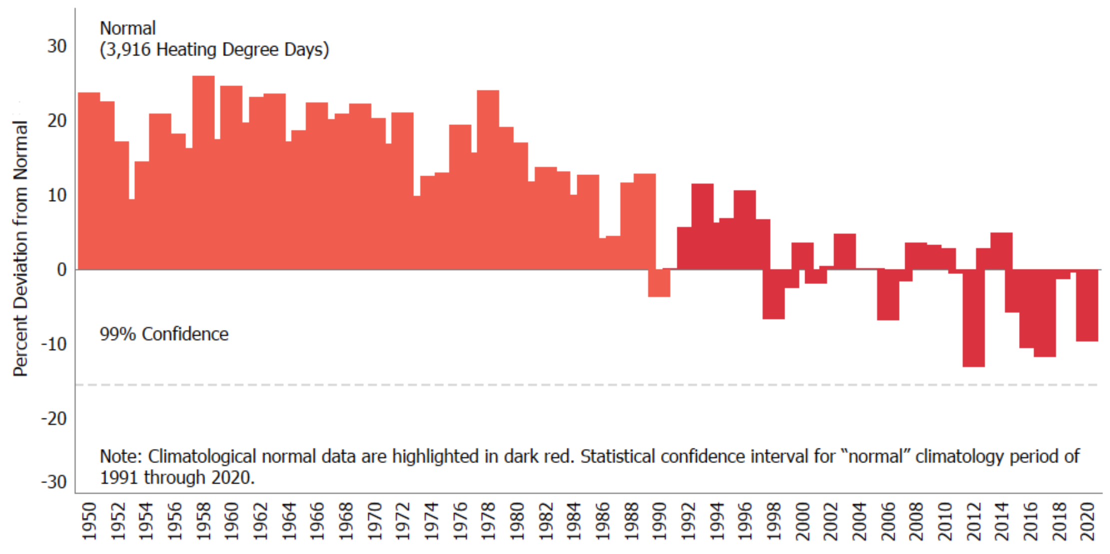
[9] See the sections entitled Stationary Combustion and Mobile Combustion in this chapter for information on non-CO_2 gas emissions from fossil fuel combustion.

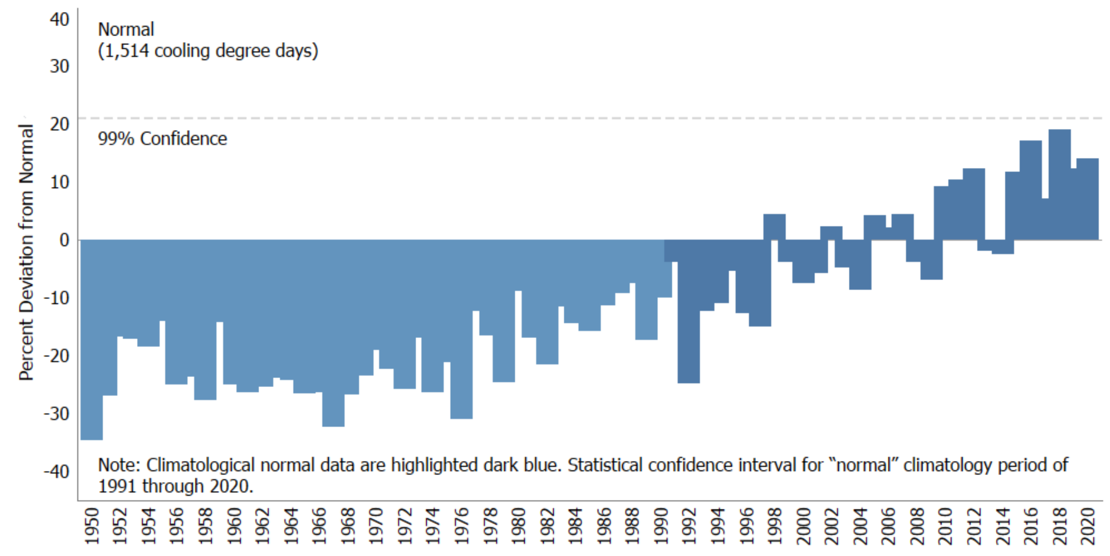
energy required for cooling, 2020 cooling degree days in the United States were 14.0 percent above normal (see Figure 3-8) (EIA 2021c).[10] The combination of warmer winter and hotter summer conditions led to overall residential and commercial energy consumption decreases of 7.5 and 9.5 percent, respectively relative to 2019.

Figure 3-7: Annual Deviations from Normal Heating Degree Days for the United States (1950–2020, Index Normal = 100)



Note: Climatological normal data are highlighted in dark red. Statistical confidence interval for "normal" climatology period of 1991 through 2020.

Figure 3-8: Annual Deviations from Normal Cooling Degree Days for the United States (1950–2020, Index Normal = 100)



Note: Climatological normal data are highlighted dark blue. Statistical confidence interval for "normal" climatology period of 1991 through 2020.

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[10] Degree days are relative measurements of outdoor air temperature. Heating degree days are deviations of the mean daily temperature below 65 degrees Fahrenheit, while cooling degree days are deviations of the mean daily temperature above 65 degrees Fahrenheit. Heating degree days have a considerably greater effect on energy demand and related emissions than do cooling degree days. Excludes Alaska and Hawaii. Normals are based on data from 1991 through 2020. The variation in these normals during this time period was ±16 percent and ±27 percent for heating and cooling degree days, respectively (99 percent confidence interval).

The carbon intensity of the electric power sector is impacted by the amount of non-fossil energy sources of electricity. The utilization (i.e., capacity factors)[11] of nuclear power plants in 2020 remained high at 93 percent. In 2020, nuclear power represented 21 percent of total electricity generation. Since 1990, the wind and solar power sectors have shown strong growth (between an observed minimum of 89 percent annual electricity generation growth to a maximum of 162 percent annual electricity generation growth) and have become relatively important electricity sources. Between 1990 and 2020, renewable energy generation (in kWh) from solar and wind energy have increased from 0.1 percent in 1990 to 11 percent in 2020 of total electricity generation, which helped drive the decrease in the carbon intensity of the electricity supply in the United States.

Stationary Combustion

The direct combustion of fuels by stationary sources in the electric power, industrial, commercial, and residential sectors represent the greatest share of U.S. greenhouse gas emissions. Table 3-7 presents CO_2 emissions from fossil fuel combustion by stationary sources. The CO_2 emitted is closely linked to the type of fuel being combusted in each sector (see Methodology section of CO_2 from Fossil Fuel Combustion). In addition to the CO_2 emitted from fossil fuel combustion, CH_4 and N_2O are emitted as well. Table 3-8 and Table 3-9 present CH_4 and N_2O emissions from the combustion of fuels in stationary sources. The CH_4 and N_2O emissions are linked to the type of fuel being combusted as well as the combustion technology (see Methodology section for CH_4 and N_2O from Stationary Combustion).

Table 3-7: CO_2 Emissions from Stationary Fossil Fuel Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2016	2017	2018	2019	2020
Electric Power	**1,820.0**	**2,400.1**	**1,808.9**	**1,732.0**	**1,752.9**	**1,606.1**	**1,439.0**
Coal	1,546.5	1,982.8	1,242.0	1,207.1	1,152.9	973.5	788.2
Natural Gas	175.4	318.9	545.0	505.6	577.4	616.0	634.3
Fuel Oil	97.5	98.0	21.5	18.9	22.2	16.2	16.2
Geothermal	0.5	0.5	0.4	0.4	0.4	0.4	0.4
Industrial	**853.7**	**851.5**	**792.7**	**790.4**	**814.1**	**816.1**	**766.3**
Coal	157.8	117.8	63.2	58.7	54.4	49.5	43.0
Natural Gas	408.8	388.6	463.9	469.5	494.0	501.6	485.5
Fuel Oil	287.1	345.0	265.7	262.2	265.7	265.0	237.8
Commercial	**228.3**	**227.1**	**231.5**	**232.0**	**245.8**	**250.7**	**226.8**
Coal	12.0	9.3	2.3	2.0	1.8	1.6	1.4
Natural Gas	142.0	162.9	170.5	173.2	192.5	192.9	173.9
Fuel Oil	74.3	54.9	58.7	56.8	51.5	56.2	51.6
Residential	**338.6**	**358.9**	**292.8**	**293.4**	**338.2**	**341.4**	**315.8**
Coal	3.0	0.8	NO	NO	NO	NO	NO
Natural Gas	237.8	262.2	238.4	241.5	273.8	275.5	256.4
Fuel Oil	97.8	95.9	54.4	51.9	64.4	65.9	59.5
U.S. Territories	**21.7**	**55.9**	**26.0**	**25.5**	**25.5**	**24.3**	**22.7**
Coal	0.5	3.0	3.3	2.3	2.6	3.6	3.1
Natural Gas	NO	1.3	3.4	2.5	3.3	3.8	2.6
Fuel Oil	21.2	51.6	19.4	20.6	19.6	16.9	16.9
Total	**3,262.2**	**3,893.5**	**3,152.0**	**3,073.3**	**3,176.5**	**3,038.6**	**2,770.6**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

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[11] The capacity factor equals generation divided by net summer capacity. Summer capacity is defined as "The maximum output that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)." Data for both the generation and net summer capacity are from EIA (2019).

Table 3-8: CH_4 Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2016	2017	2018	2019	2020
Electric Power	**0.4**	**0.9**	**1.2**	**1.1**	**1.2**	**1.3**	**1.2**
Coal	0.3	0.4	0.2	0.2	0.2	0.2	0.2
Fuel Oil	+	+	+	+	+	+	+
Natural gas	0.1	0.5	0.9	0.9	1.0	1.1	1.1
Wood	+	+	+	+	+	+	+
Industrial	**1.8**	**1.7**	**1.6**	**1.5**	**1.5**	**1.5**	**1.4**
Coal	0.4	0.3	0.2	0.2	0.1	0.1	0.1
Fuel Oil	0.2	0.2	0.2	0.2	0.2	0.2	0.1
Natural gas	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Wood	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Commercial	**1.1**	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Natural gas	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Wood	0.5	0.5	0.6	0.6	0.6	0.6	0.6
Residential	**5.2**	**4.1**	**3.9**	**3.8**	**4.6**	**4.7**	**4.1**
Coal	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Fuel Oil	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Natural Gas	0.5	0.6	0.5	0.5	0.6	0.6	0.6
Wood	4.1	3.1	3.2	3.1	3.7	3.9	3.3
U.S. Territories	**+**	**0.1**	**+**	**+**	**+**	**+**	**+**
Coal	+	+	+	+	+	+	+
Fuel Oil	+	0.1	+	+	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**8.6**	**7.8**	**7.9**	**7.7**	**8.6**	**8.8**	**7.9**

\+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-9: N_2O Emissions from Stationary Combustion (MMT CO_2 Eq.)

Sector/Fuel Type	1990	2005	2016	2017	2018	2019	2020
Electric Power	**20.5**	**30.1**	**26.2**	**24.8**	**24.4**	**21.1**	**19.7**
Coal	20.1	28.0	22.4	21.2	20.3	16.7	15.2
Fuel Oil	0.1	0.1	+	+	+	+	+
Natural Gas	0.3	1.9	3.8	3.6	4.1	4.4	4.5
Wood	+	+	+	+	+	+	+
Industrial	**3.1**	**2.9**	**2.6**	**2.5**	**2.5**	**2.5**	**2.3**
Coal	0.7	0.6	0.3	0.3	0.3	0.2	0.2
Fuel Oil	0.5	0.5	0.4	0.4	0.4	0.4	0.3
Natural Gas	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Wood	1.6	1.6	1.7	1.6	1.6	1.6	1.5
Commercial	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Coal	0.1	+	+	+	+	+	+
Fuel Oil	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Residential	**1.0**	**0.9**	**0.8**	**0.8**	**0.9**	**0.9**	**0.8**
Coal	+	+	0.0	0.0	0.0	0.0	0.0
Fuel Oil	0.2	0.2	0.1	0.1	0.2	0.2	0.2

Natural Gas	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Wood	0.7	0.5	0.5	0.5	0.6	0.6	0.5
U.S. Territories	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Coal	+	+	+	+	+	+	+
Fuel Oil	0.1	0.1	+	0.1	+	+	+
Natural Gas	NO	+	+	+	+	+	+
Wood	NE	NE	NE	NE	NE	NE	NE
Total	**25.1**	**34.4**	**30.0**	**28.4**	**28.2**	**24.9**	**23.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Fossil Fuel Combustion Emissions by Sector

Table 3-10 provides an overview of the CO_2, CH_4, and N_2O emissions from fossil fuel combustion by sector, including transportation, electric power, industrial, residential, commercial, and U.S. territories.

Table 3-10: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by Sector (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation	**1,520.0**	**1,903.9**	**1,781.3**	**1,802.6**	**1,834.4**	**1,836.2**	**1,591.6**
CO_2	1,468.9	1,858.6	1,757.6	1,780.0	1,812.8	1,813.8	1,572.0
CH_4	6.5	4.0	2.6	2.6	2.5	2.5	2.2
N_2O	44.6	41.4	21.1	20.1	19.2	20.0	17.4
Electric Power	**1,840.9**	**2,431.0**	**1,836.2**	**1,757.9**	**1,778.5**	**1,628.5**	**1,460.0**
CO_2	1,820.0	2,400.1	1,808.9	1,732.0	1,752.9	1,606.1	1,439.0
CH_4	0.4	0.9	1.2	1.1	1.2	1.3	1.2
N_2O	20.5	30.1	26.2	24.8	24.4	21.1	19.7
Industrial	**858.6**	**856.2**	**796.9**	**794.5**	**818.2**	**820.1**	**770.1**
CO_2	853.7	851.5	792.7	790.4	814.1	816.1	766.3
CH_4	1.8	1.7	1.6	1.5	1.5	1.5	1.4
N_2O	3.1	2.9	2.6	2.5	2.5	2.5	2.3
Residential	**344.9**	**363.8**	**297.4**	**298.0**	**343.7**	**347.1**	**320.7**
CO_2	338.6	358.9	292.8	293.4	338.2	341.4	315.8
CH_4	5.2	4.1	3.9	3.8	4.6	4.7	4.1
N_2O	1.0	0.9	0.8	0.8	0.9	0.9	0.8
Commercial	**229.8**	**228.6**	**233.1**	**233.5**	**247.4**	**252.3**	**228.3**
CO_2	228.3	227.1	231.5	232.0	245.8	250.7	226.8
CH_4	1.1	1.1	1.2	1.2	1.2	1.2	1.2
N_2O	0.4	0.3	0.3	0.3	0.3	0.3	0.3
U.S. Territories[a]	**21.8**	**56.1**	**26.1**	**25.6**	**25.6**	**24.4**	**22.7**
Total	**4,815.9**	**5,839.6**	**4,971.2**	**4,912.1**	**5,047.8**	**4,908.4**	**4,393.4**

[a] U.S. Territories are not apportioned by sector, and emissions shown in the table are total greenhouse gas emissions from all fuel combustion sources.

Note: Totals may not sum due to independent rounding.

Other than greenhouse gases CO_2, CH_4, and N_2O, gases emitted from stationary combustion include the greenhouse gas precursors nitrogen oxides (NO_x), CO, NMVOCs, and SO_2. Methane and N_2O emissions from stationary combustion sources depend upon fuel characteristics, size and vintage of combustion device, along with combustion technology, pollution control equipment, ambient environmental conditions, and operation and maintenance practices. Nitrous oxide emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed.

Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.

Mobile combustion also produces emissions of CH_4, N_2O, and greenhouse gas precursors including NO_x, CO, and NMVOCs. As with stationary combustion, N_2O and NO_x emissions from mobile combustion are closely related to fuel characteristics, air-fuel mixes, combustion temperatures, and the use of pollution control equipment. Nitrous oxide from mobile sources, in particular, can be formed by the catalytic processes used to control NO_x, CO, and hydrocarbon emissions. Carbon monoxide emissions from mobile combustion are significantly affected by combustion efficiency and the presence of post-combustion emission controls. Carbon monoxide emissions are highest when air-fuel mixtures have less oxygen than required for complete combustion. These emissions occur especially in vehicle idle, low speed, and cold start conditions. Methane and NMVOC emissions from motor vehicles are a function of the CH_4 content of the motor fuel, the amount of hydrocarbons passing uncombusted through the engine, and any post-combustion control of hydrocarbon emissions (such as catalytic converters).

An alternative method of presenting combustion emissions is to allocate emissions associated with electric power to the sectors in which it is used. Four end-use sectors are defined: transportation, industrial, residential, and commercial. In Table 3-11 below, electric power emissions have been distributed to each end-use sector based upon the sector's share of national electricity use, with the exception of CH_4 and N_2O from transportation electricity use.[12] Emissions from U.S. Territories are also calculated separately due to a lack of end-use-specific consumption data.[13] This method assumes that emissions from combustion sources are distributed across the four end-use sectors based on the ratio of electricity use in that sector. The results of this alternative method are presented in Table 3-11.

Table 3-11: CO_2, CH_4, and N_2O Emissions from Fossil Fuel Combustion by End-Use Sector with Electricity Emissions Distributed (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation	**1,523.1**	**1,908.6**	**1,785.5**	**1,806.9**	**1,839.0**	**1,840.9**	**1,596.3**
CO_2	1,472.0	1,863.3	1,761.8	1,784.3	1,817.4	1,818.5	1,576.7
CH_4	6.5	4.0	2.6	2.6	2.5	2.5	2.2
N_2O	44.6	41.4	21.1	20.1	19.2	20.0	17.4
Industrial	**1,552.9**	**1,602.0**	**1,322.4**	**1,306.4**	**1,326.7**	**1,291.9**	**1,185.6**
CO_2	1,540.1	1,587.8	1,310.3	1,294.8	1,315.3	1,281.4	1,175.8
CH_4	2.0	2.0	1.9	1.9	1.9	1.9	1.8
N_2O	10.8	12.2	10.1	9.8	9.5	8.6	7.9
Residential	**944.4**	**1,230.9**	**960.8**	**924.3**	**995.3**	**938.8**	**873.5**
CO_2	931.3	1,214.9	946.2	910.5	980.4	925.0	860.6
CH_4	5.4	4.4	4.3	4.2	5.0	5.2	4.5
N_2O	7.7	11.6	10.3	9.6	9.9	8.6	8.3
Commercial	**773.7**	**1,041.9**	**876.3**	**848.8**	**861.1**	**812.5**	**715.3**
CO_2	766.0	1,030.1	865.2	838.2	850.7	803.2	706.8
CH_4	1.2	1.4	1.6	1.6	1.6	1.7	1.6
N_2O	6.5	10.4	9.5	9.0	8.8	7.6	6.9
U.S. Territories[a]	**21.8**	**56.1**	**26.1**	**25.6**	**25.6**	**24.4**	**22.7**
Total	**4,815.9**	**5,839.6**	**4,971.2**	**4,912.1**	**5,047.8**	**4,908.4**	**4,393.4**

[a] U.S. Territories are not apportioned by sector, and emissions are total greenhouse gas emissions from all fuel combustion sources.

Notes: Totals may not sum due to independent rounding. Emissions from fossil fuel combustion by electric power are allocated based on aggregate national electricity use by each end-use sector.

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[12] Separate calculations are performed for transportation-related CH_4 and N_2O. The methodology used to calculate these emissions is discussed in the Mobile Combustion section.

[13] U.S. Territories consumption data that are obtained from EIA are only available at the aggregate level and cannot be broken out by end-use sector. The distribution of emissions to each end-use sector for the 50 states does not apply to territories data.

Electric Power Sector

The process of generating electricity is the largest stationary source of CO_2 emissions in the United States, representing 30.5 percent of total CO_2 emissions from all CO_2 emissions sources across the United States. Methane and N_2O accounted for a small portion of total greenhouse gas emissions from electric power, representing 0.1 percent and 1.4 percent, respectively. Electric power also accounted for 33.1 percent of CO_2 emissions from fossil fuel combustion in 2020. Methane and N_2O from electric power represented 12.3 and 48.6 percent of total CH_4 and N_2O emissions from fossil fuel combustion in 2020, respectively.

For the underlying energy data used in this chapter, the Energy Information Administration (EIA) places electric power generation into three functional categories: the electric power sector, the commercial sector, and the industrial sector. The energy use and emissions associated with the electric power sector are included here. The electric power sector consists of electric utilities and independent power producers whose primary business is the production of electricity. This includes both regulated utilities and non-utilities (e.g., independent power producers, qualifying co-generators, and other small power producers). Energy use and emissions associated with electric generation in the commercial and industrial sectors is reported in those other sectors where the producer of the power indicates that its primary business is something other than the production of electricity.[14]

Total greenhouse gas emissions from the electric power sector have decreased by 20.7 percent since 1990. From 1990 to 2007, electric power sector emissions increased by 33 percent, driven by a significant increase in electricity demand (39 percent) while the carbon intensity of electricity generated showed a minor increase (0.3 percent). From 2008 to 2020, as electricity demand decreased by 0.4 percent, electric power sector emissions decreased by 39 percent, driven by a significant drop (31 percent) in the carbon intensity of electricity generated. Overall, the carbon intensity of the electric power sector, in terms of CO_2 Eq. per QBtu, decreased by 19 percent from 1990 to 2020 with additional trends detailed in Box 3-4. This decoupling of electric power generation and the resulting CO_2 emissions is shown in Figure 3-9. This recent decarbonization of the electric power sector is a result of several key drivers.

Coal-fired electric generation (in kilowatt-hours [kWh]) decreased from 54 percent of generation in 1990 to 20 percent in 2020.[15] This corresponded with an increase in natural gas generation and renewable energy generation, largely from wind and solar energy. Natural gas generation (in kWh) represented 11 percent of electric power generation in 1990 and increased over the 31-year period to represent 39 percent of electric power sector generation in 2020 (see Table 3-12). Natural gas has a much lower carbon content than coal and is generated in power plants that are generally more efficient in terms of kWh produced per Btu of fuel combusted, which has led to lower emissions as natural gas replaces coal-powered electricity generation. Natural gas and coal used in the U.S. in 2020 had an average carbon content of 14.43 MMT C/QBtu and 26.12 MMT C/QBtu respectively.

Table 3-12: Electric Power Generation by Fuel Type (Percent)

Fuel Type	1990	2005	2016	2017	2018	2019	2020
Coal	54.1%	51.1%	31.4%	30.9%	28.4%	24.2%	19.9%
Natural Gas	10.7%	17.5%	32.7%	30.9%	34.0%	37.3%	39.5%
Nuclear	19.9%	20.0%	20.6%	20.8%	20.1%	20.4%	20.5%
Renewables	11.3%	8.3%	14.7%	16.8%	16.8%	17.6%	19.5%
Petroleum	4.1%	3.0%	0.6%	0.5%	0.6%	0.4%	0.4%
Other Gases[a]	+%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Net Electricity Generation (Billion kWh)[b]	*2,905*	*3,902*	*3,917*	*3,877*	*4,017*	*3,963*	*3,849*

+ Does not exceed 0.05 percent.

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[14] Utilities primarily generate power for the U.S. electric grid for sale to retail customers. Non-utilities typically generate electricity for sale on the wholesale electricity market (e.g., to utilities for distribution and resale to retail customers). Where electricity generation occurs outside the EIA-defined electric power sector, it is typically for the entity's own use.

[15] Values represent electricity *net* generation from the electric power sector (EIA 2022a).

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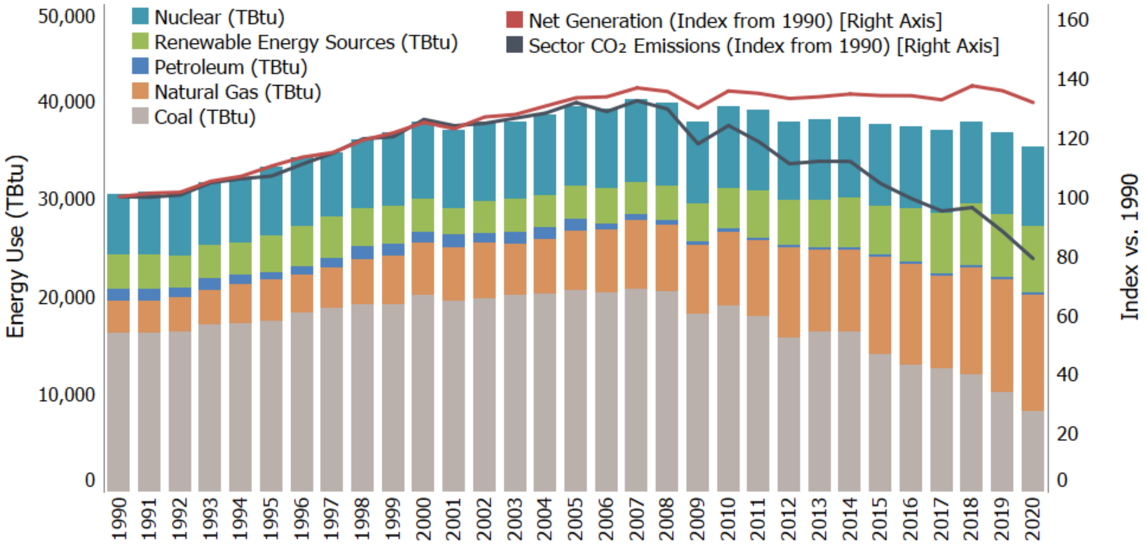
[a] Other gases include blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

[b] Represents net electricity generation from the electric power sector. Excludes net electricity generation from commercial and industrial combined-heat-and-power and electricity-only plants. Does not include electricity generation from purchased steam as the fuel used to generate the steam cannot be determined.

In 2020, CO_2 emissions from the electric power sector decreased by 10.4 percent relative to 2019. This decrease in CO_2 emissions was primarily driven by a decrease in coal and petroleum consumed to produce electricity in the electric power sector as well as a decrease in electricity demand (2.5 percent reduction in retail sales). Consumption of coal for electric power decreased by 19.2 percent while consumption of natural gas increased 2.9 percent from 2019 to 2020. There has also been a rapid increase in renewable energy electricity generation in the electric power sector in recent years. Electricity generation from renewable sources increased by 8 percent from 2019 to 2020 (see Table 3-12). The decrease in coal-powered electricity generation and increase in natural gas and renewable energy electricity generation contributed to a decoupling of emissions trends from electric power generation trends over the recent time series (see Figure 3-9).

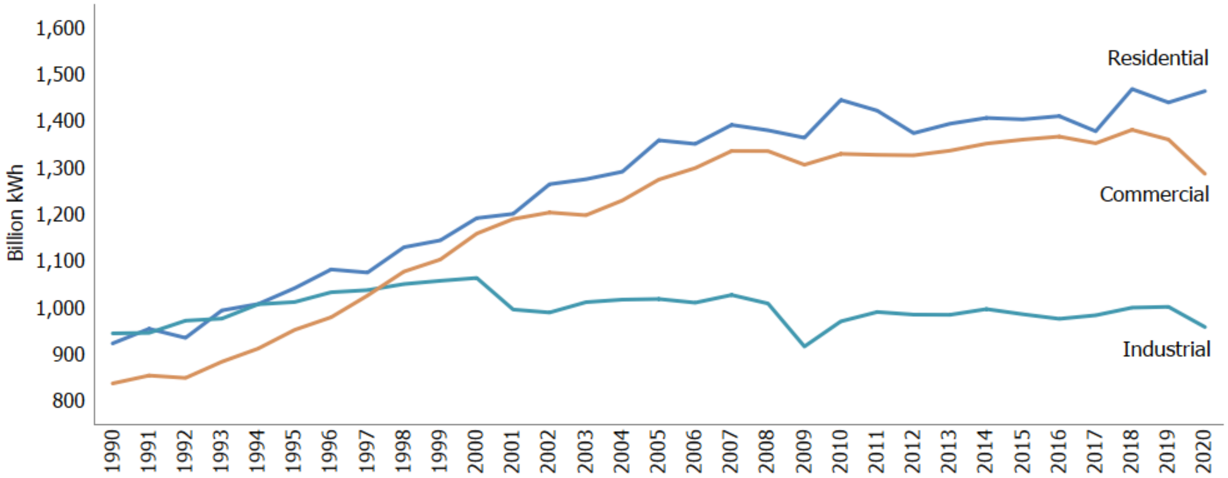
Decreases in natural gas prices and the associated increase in natural gas generation, particularly between 2005 and 2020, was one of the main drivers of the recent fuel switching and decrease in electric power sector carbon intensity. During this time period, the cost of natural gas (in $/MMBtu) decreased by 64 percent while the cost of coal (in $/MMBtu) increased by 66 percent (EIA 2021c). Also, between 1990 and 2020, renewable energy generation (in kWh) from wind and solar energy increased from 0.1 percent of total generation in 1990 to 11 percent in 2020, which also helped drive the decrease in electric power sector carbon intensity. This decrease in carbon intensity occurred even as total electricity retail sales increased 37 percent, from 2,713 billion kWh in 1990 to 3,718 billion kWh in 2020.

Figure 3-9: Fuels Used in Electric Power Generation and Total Electric Power Sector CO_2 Emissions



Electricity was used primarily in the residential, commercial, and industrial end-use sectors for lighting, heating, electric motors, appliances, electronics, and air conditioning (see Figure 3-10). Note that transportation is an end-use sector as well but is not shown in Figure 3-10 due to the sector's relatively low percentage of electricity use. Table 3-13 provides a break-out of CO_2 emissions from electricity use in the transportation end-use sector.

Figure 3-10: Electric Power Retail Sales by End-Use Sector



In 2020, electricity sales to the residential and commercial end-use sectors, as presented in Figure 3-10, increased by 1.7 percent and decreased by 5.4 percent relative to 2019, respectively. Electricity sales to the industrial sector in 2020 decreased by approximately 4.3 percent relative to 2019. The sections below describe end-use sector energy use in more detail. Overall, in 2020, the amount of electricity retail sales (in kWh) decreased by 2.5 percent relative to 2019. These electricity sales trends between 2019 and 2020 were likely impacted by the COVID-19 pandemic as people staying at home more increased electricity sales in the residential sector while decreasing sales in other sectors.

Industrial Sector

Industrial sector CO_2, CH_4, and N_2O emissions accounted for 18, 14, and 6 percent of CO_2, CH_4, and N_2O emissions from fossil fuel combustion, respectively in 2020. Carbon dioxide, CH_4, and N_2O emissions resulted from the direct consumption of fossil fuels for steam and process heat production.

The industrial end-use sector, per the underlying energy use data from EIA, includes activities such as manufacturing, construction, mining, and agriculture. The largest of these activities in terms of energy use is manufacturing, of which six industries—Petroleum Refineries, Chemicals, Paper, Primary Metals, Food, and Nonmetallic Mineral Products—represent the majority of the energy use (EIA 2021c; EIA 2009b).

There are many dynamics that impact emissions from the industrial sector including economic activity, changes in the make-up of the industrial sector, changes in the emissions intensity of industrial processes, and weather-related impacts on heating and cooling of industrial buildings.[16] Structural changes within the U.S. economy that lead to shifts in industrial output away from energy-intensive manufacturing products to less energy-intensive products (e.g., from steel to computer equipment) have had a significant effect on industrial emissions.

From 2019 to 2020, total industrial production and manufacturing output decreased by 7.2 percent (FRB 2021). Over this period, output decreased slightly across all production indices including Food, Nonmetallic Mineral Products, Paper, Petroleum Refineries, Chemicals, and Primary Metals (see Figure 3-11). From 2019 to 2020, total energy use in the industrial sector decreased by 5.3 percent partially as a result of reductions in economic and manufacturing activity due to the COVID-19 pandemic. Due to the relative increases and decreases of individual indices there was a decrease in natural gas and a decrease in electricity used by the sector (see Figure 3-12). In

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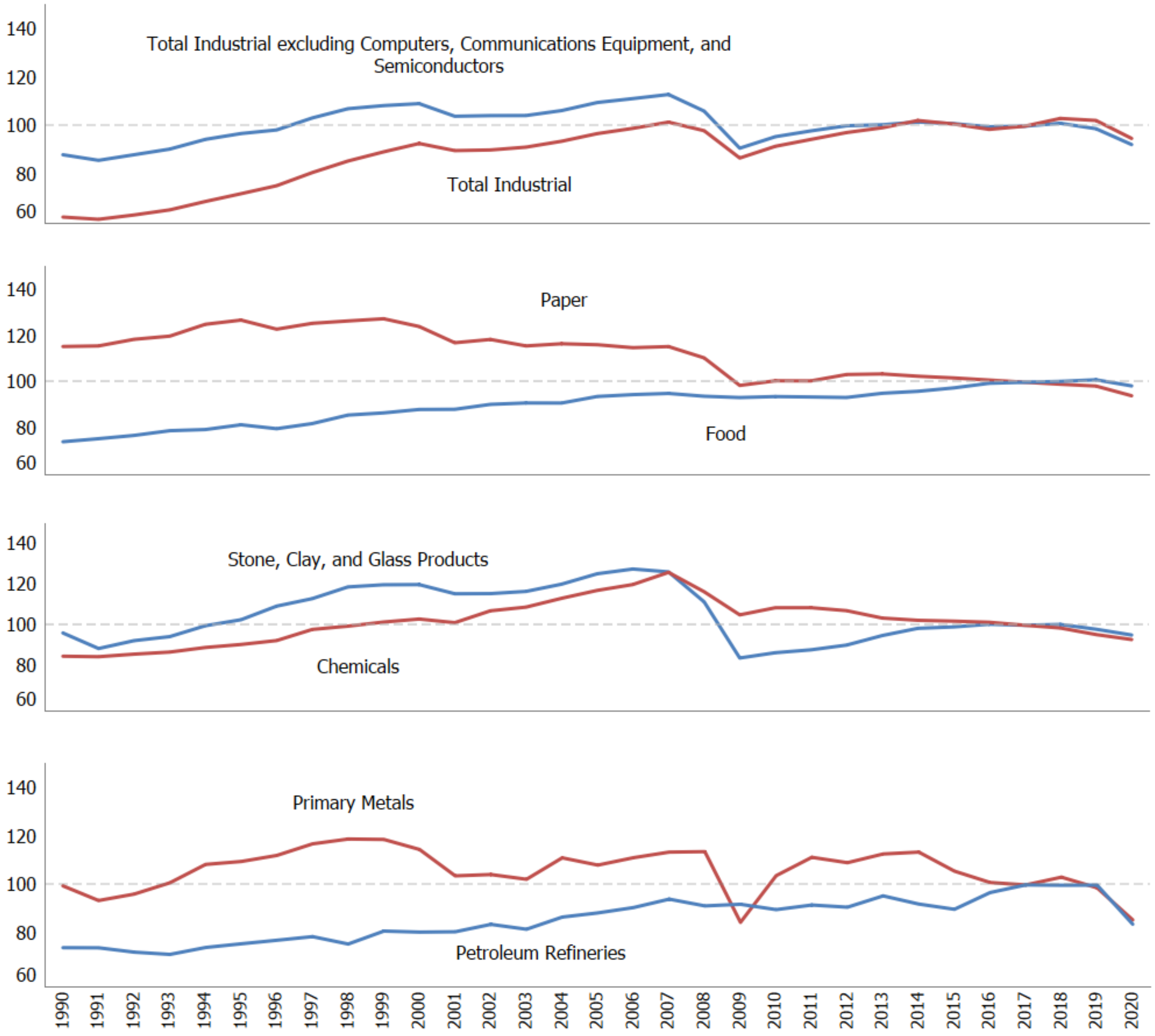
[16] Some commercial customers are large enough to obtain an industrial price for natural gas and/or electricity and are consequently grouped with the industrial end-use sector in U.S. energy statistics. These misclassifications of large commercial customers likely cause the industrial end-use sector to appear to be more sensitive to weather conditions.

2020, CO_2, CH_4, and N_2O emissions from fossil fuel combustion and electricity use within the industrial end-use sector totaled 1,185.6 MMT CO_2 Eq., an 8.2 percent decrease from 2019 emissions.

Through EPA's Greenhouse Gas Reporting Program (GHGRP), specific industrial sector trends can be discerned from the overall total EIA industrial fuel consumption data used for these calculations. For example, from 2019 to 2020, the underlying EIA data showed decreased consumption of coal and natural gas in the industrial sector. The GHGRP data highlights that several industries contributed to these trends, including chemical manufacturing; pulp, paper and print; food processing, beverages and tobacco; minerals manufacturing; and agriculture-forest-fisheries.[17]

Figure 3-11: Industrial Production Indices (Index 2017=100)



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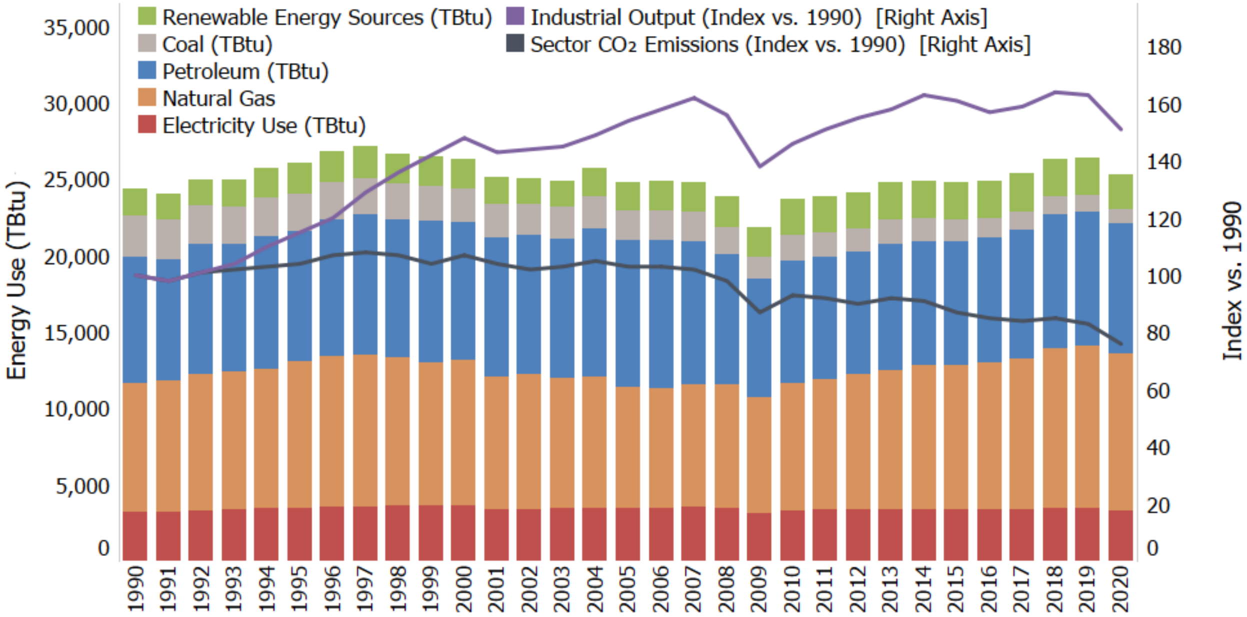
[17] Further details on industrial sector combustion emissions are provided by EPA's GHGRP. See http://ghgdata.epa.gov/ghgp/main.do.

Figure 3-12: Fuels and Electricity Used in Industrial Sector, Industrial Output, and Total Sector CO_2 Emissions (Including Electricity)



Despite the growth in industrial output (52 percent) and the overall U.S. economy (96 percent) from 1990 to 2020, direct CO_2 emissions from fossil fuel combustion in the industrial sector decreased by 10.2 percent over the same time series (see Figure 3-12). A number of factors are assumed to result in decoupling of growth in industrial output from industrial greenhouse gas emissions, for example: (1) more rapid growth in output from less energy-intensive industries relative to traditional manufacturing industries, and (2) energy-intensive industries such as steel are employing new methods, such as electric arc furnaces, that are less carbon intensive than the older methods.

Box 3-3: Uses of Greenhouse Gas Reporting Program Data and Improvements in Reporting Emissions from Industrial Sector Fossil Fuel Combustion

As described in the calculation methodology, total fossil fuel consumption for each year is based on aggregated end-use sector consumption published by the EIA. The availability of facility-level combustion emissions through EPA's GHGRP has provided an opportunity to better characterize the industrial sector's energy consumption and emissions in the United States, through a disaggregation of EIA's industrial sector fuel consumption data from select industries.

For GHGRP 2010 through 2020 reporting years, facility-level fossil fuel combustion emissions reported through EPA's GHGRP were categorized and distributed to specific industry types by utilizing facility-reported NAICS codes (as published by the U.S. Census Bureau). As noted previously in this report, the definitions and provisions for reporting fuel types in EPA's GHGRP include some differences from the Inventory's use of EIA national fuel statistics to meet the UNFCCC reporting guidelines. The IPCC has provided guidance on aligning facility-level reported fuels and fuel types published in national energy statistics, which guided this exercise.[18]

As with previous Inventory reports, the current effort represents an attempt to align, reconcile, and coordinate the facility-level reporting of fossil fuel combustion emissions under EPA's GHGRP with the national-level approach presented in this report. Consistent with recommendations for reporting the Inventory to the

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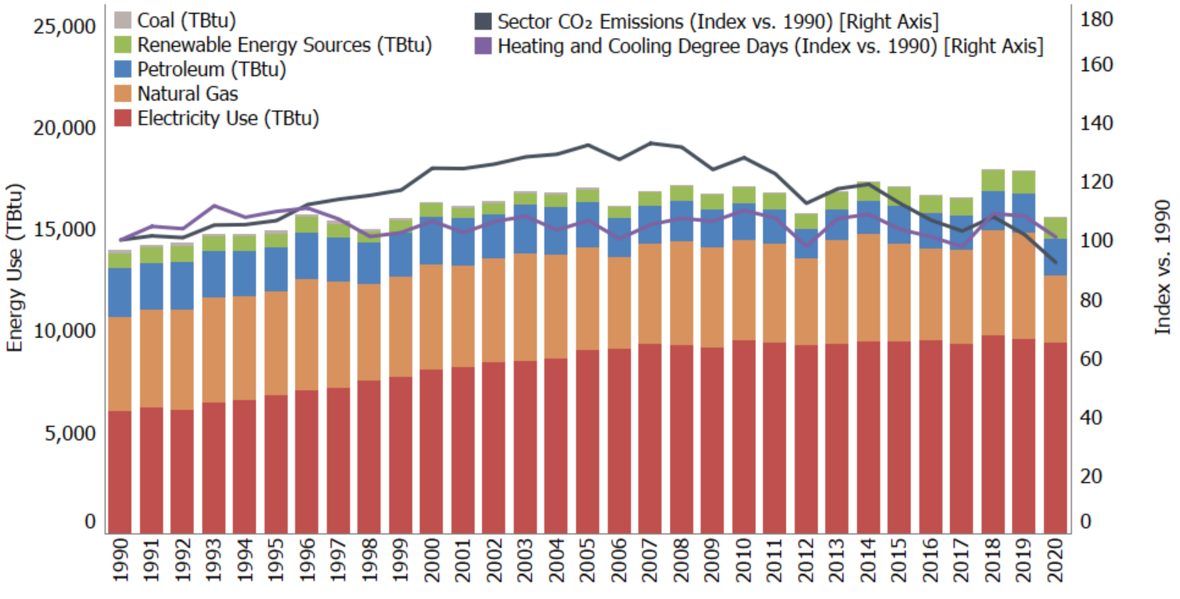
[18] See Section 4 "Use of Facility-Level Data in Good Practice National Greenhouse Gas Inventories" of the IPCC meeting report, and specifically the section on using facility-level data in conjunction with energy data, at http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

UNFCCC, progress was made on certain fuel types for specific industries and has been included in the CRF tables that are submitted to the UNFCCC along with this report.[19] The efforts in reconciling fuels focus on standard, common fuel types (e.g., natural gas, distillate fuel oil) where the fuels in EIA's national statistics aligned well with facility-level GHGRP data. For these reasons, the current information presented in the Common Reporting Format (CRF) tables should be viewed as an initial attempt at this exercise. Additional efforts will be made for future Inventory reports to improve the mapping of fuel types and examine ways to reconcile and coordinate any differences between facility-level data and national statistics. The current analysis includes the full time series presented in the CRF tables. Analyses were conducted linking GHGRP facility-level reporting with the information published by EIA in its MECS data in order to disaggregate the full 1990 through 2020 time period in the CRF tables. It is believed that the current analysis has led to improvements in the presentation of data in the Inventory, but further work will be conducted, and future improvements will be realized in subsequent Inventory reports. This includes incorporating the latest MECS data as it becomes available.

Residential and Commercial Sectors

Emissions from the residential and commercial sectors have generally decreased since 2005. Short-term trends are often correlated with seasonal fluctuations in energy use caused by weather conditions, rather than prevailing economic conditions. Population growth and a trend towards larger houses has led to increasing energy use over the time series, while population migration to warmer areas and improved energy efficiency and building insulation have slowed the increase in energy use in recent years. Starting in around 2014, energy use and emissions begin to decouple due to decarbonization of the electric power sector (see Figure 3-13).

Figure 3-13: Fuels and Electricity Used in Residential and Commercial Sectors, Heating and Cooling Degree Days, and Total Sector CO_2 Emissions (Including Electricity)



In 2020 the residential and commercial sectors accounted for 7 and 5 percent of CO_2 emissions from fossil fuel combustion, respectively; 40 and 12 percent of CH_4 emissions from fossil fuel combustion, respectively; and 2 and 1 percent of N_2O emissions from fossil fuel combustion, respectively. Emissions from these sectors were largely due to the direct consumption of natural gas and petroleum products, primarily for heating and cooking needs. Coal consumption was a minor component of energy use in the commercial sector and did not contribute to any

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[19] See https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

energy use in the residential sector. In 2020, total emissions (CO_2, CH_4, and N_2O) from fossil fuel combustion and electricity use within the residential and commercial end-use sectors were 873.5 MMT CO_2 Eq. and 715.3 MMT CO_2 Eq., respectively. Total CO_2, CH_4, and N_2O emissions from combined fossil fuel combustion and electricity use within the residential and commercial end-use sectors decreased by 7.0 and 12.0 percent from 2019 to 2020, respectively. A decrease in heating degree days (9.4 percent) reduced energy demand for heating in the residential and commercial sectors. This was partially offset by a 1.5 percent increase in cooling degree days compared to 2019, which impacted demand for air conditioning in the residential and commercial sectors. This, combined with people staying home in response to the COVID-19 pandemic, resulted in a 1.7 percent increase in residential sector electricity use. From 2019 to 2020 the COVID-19 pandemic reduced economic activity which contributed to 9.6 percent lower direct energy use in the commercial sector. In addition, a shift toward energy efficient products and more stringent energy efficiency standards for household equipment has contributed to a decrease in energy demand in households (EIA 2020g), resulting in a decrease in energy-related emissions. In the long term, the residential sector is also affected by population growth, migration trends toward warmer areas, and changes in total housing units and building attributes (e.g., larger sizes and improved insulation).

In 2020, combustion emissions from natural gas consumption represented 81 and 77 percent of the direct fossil fuel CO_2 emissions from the residential and commercial sectors, respectively. Carbon dioxide emissions from natural gas combustion in the residential and commercial sectors in 2020 decreased by 6.9 percent and 9.9 percent from 2019 to 2020, respectively.

U.S. Territories

Emissions from U.S. Territories are based on the fuel consumption in American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other outlying U.S. Pacific Islands. As described in the Methodology section of CO_2 from Fossil Fuel Combustion, this data is collected separately from the sectoral-level data available for the general calculations. As sectoral information is not available for U.S. Territories, CO_2, CH_4, and N_2O emissions are not presented for U.S. Territories in the tables above by sector, though the emissions will occur across all sectors and sources including stationary, transportation and mobile combustion sources. Due to data availability limitations, 2020 energy consumption for U.S. Territories for petroleum is proxied to 2019 consumption data.

Transportation Sector and Mobile Combustion

This discussion of transportation emissions follows the alternative method of presenting combustion emissions by allocating emissions associated with electricity generation to the transportation end-use sector, as presented in Table 3-11. Table 3-10 presents direct CO_2, CH_4, and N_2O emissions from all transportation sources (i.e., excluding emissions allocated to electricity consumption in the transportation end-use sector).

The transportation end-use sector and other mobile combustion accounted for 1,596.4 MMT CO_2 Eq. in 2020, which represented 35 percent of CO_2 emissions, 22 percent of CH_4 emissions, and 43 percent of N_2O emissions from fossil fuel combustion, respectively.[20] Fuel purchased in the United States for international aircraft and marine travel accounted for an additional 70.3 MMT CO_2 Eq. in 2020; these emissions are recorded as international bunkers and are not included in U.S. totals according to UNFCCC reporting protocols.

Transportation End-Use Sector

From 1990 to 2019, transportation emissions from fossil fuel combustion increased by 20.9 percent, followed by a decline of 13.3 percent from 2019 to 2020. Overall, from 1990 to 2020, transportation emissions from fossil fuel combustion increased by 4.8 percent. The increase in transportation emissions from fossil fuel combustion from 1990 to 2019 was due, in large part, to increased demand for travel (see Figure 3-14). The number of vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) increased 47.5 percent from

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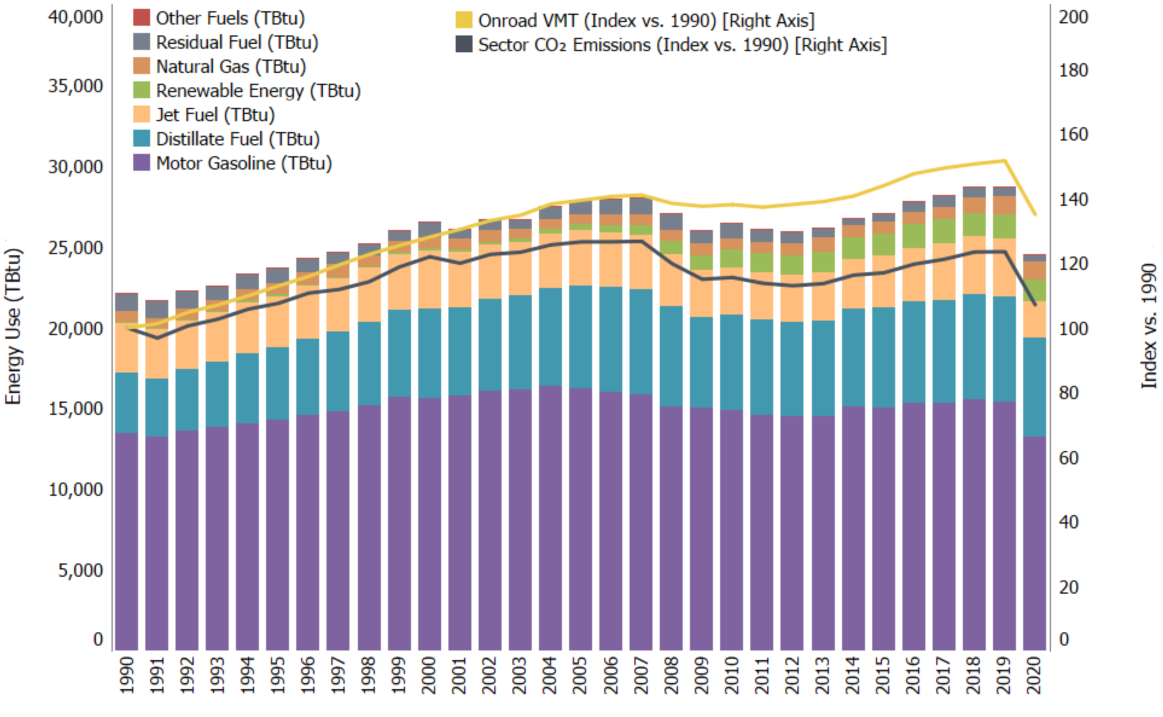
[20] Note that these totals include CO_2, CH_4 and N_2O emissions from some sources in the U.S. Territories (ships and boats, recreational boats, non-transportation mobile sources) and CH_4 and N_2O emissions from transportation rail electricity.

1990 to 2019,[21] as a result of a confluence of factors including population growth, economic growth, urban sprawl, and periods of low fuel prices. The drop in transportation emissions from fossil fuel combustion from 2019 to 2020 was primarily the result of the COVID-19 pandemic and associated restrictions, such as people working from home and traveling less. During this period, the number of vehicle miles traveled (VMT) by light-duty motor vehicles (passenger cars and light-duty trucks) decreased by 12.2 percent.

Commercial aircraft emissions decreased by 32 percent between 2019 and 2020 and have decreased 35 percent since 2007 (FAA 2022 and DOT 1991 through 2021).[22] Decreases in jet fuel emissions (excluding bunkers) started in 2007 due in part to improved operational efficiency that results in more direct flight routing, improvements in aircraft and engine technologies to reduce fuel burn and emissions, and the accelerated retirement of older, less fuel-efficient aircraft; however, the sharp decline in commercial aircraft emissions from 2019 to 2020 is primarily due to COVID-19 impacts on scheduled passenger air travel.

Almost all of the energy consumed for transportation was supplied by petroleum-based products, with more than half being related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. The primary driver of transportation-related emissions was CO_2 from fossil fuel combustion, which increased by 24 percent from 1990 to 2019, followed by a reduction of 13 percent from 2019 to 2020. Annex 3.2 presents the total emissions from all transportation and mobile sources, including CO_2, N_2O, CH_4, and HFCs.

Figure 3-14: Fuels Used in Transportation Sector, Onroad VMT, and Total Sector CO_2 Emissions



Notes: Distillate fuel, residual fuel, and jet fuel include adjustments for international bunker fuels. Distillate fuel and motor gasoline include adjustments for the sectoral allocation of these fuels. Other Fuels includes aviation gasoline and propane.
Source: Information on fuel consumption was obtained from EIA (2022).

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[21] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2020 time period. In absence of these method changes, light-duty VMT growth between 1990 and 2020 would likely have been higher.

[22] Commercial aircraft consists of passenger aircraft, cargo, and other chartered flights.

Transportation Fossil Fuel Combustion CO_2 Emissions

Domestic transportation CO_2 emissions increased by 7 percent (104.7 MMT CO_2) between 1990 and 2020, an annualized increase of 0.2 percent. This includes a 24 percent increase in CO_2 emissions between 1990 and 2019, followed by a 13 percent decline between 2019 and 2020. Among domestic transportation sources in 2020, light-duty vehicles (including passenger cars and light-duty trucks) represented 57 percent of CO_2 emissions from fossil fuel combustion, medium- and heavy-duty trucks and buses 27 percent, commercial aircraft 6 percent, and other sources 10 percent. See Table 3-13 for a detailed breakdown of transportation CO_2 emissions by mode and fuel type.

Almost all of the energy consumed by the transportation sector is petroleum-based, including motor gasoline, diesel fuel, jet fuel, and residual oil. Carbon dioxide emissions from the combustion of ethanol and biodiesel for transportation purposes, along with the emissions associated with the agricultural and industrial processes involved in the production of biofuel, are captured in other Inventory sectors.[23] Ethanol consumption by the transportation sector has increased from 0.7 billion gallons in 1990 to 11.7 billion gallons in 2020, while biodiesel consumption has increased from 0.01 billion gallons in 2001 to 1.9 billion gallons in 2020. For additional information, see Section 3.10 on biofuel consumption at the end of this chapter and Table A-76 in Annex 3.2.

Carbon dioxide emissions from passenger cars and light-duty trucks increased from 924.5 MMT CO_2 in 1990 to 1052.1 CO_2 in 2019, then dropped to 902.8 MMT CO_2 in 2020, due to the COVID-19 pandemic and associated restrictions. Overall, CO_2 emissions from passenger cars and light-duty trucks decreased 2 percent (-21.7 MMT CO_2) from 1990 to 2020. The 14 percent (127.6 MMT CO_2) increase in CO_2 emissions from passenger cars and light-duty trucks from 1990 to 2019 was due, in large part, to increased demand for travel as fleet-wide light-duty vehicle fuel economy was relatively stable (average new vehicle fuel economy declined slowly from 1990 through 2004 and then increased more rapidly from 2005 through 2020). Carbon dioxide emissions from passenger cars and light-duty trucks peaked at 1,154.7 MMT CO_2 in 2004, and since then have declined about 22 percent. The decline in new light-duty vehicle fuel economy between 1990 and 2004 (Figure 3-15) reflects the increasing market share of light-duty trucks, which grew from about 30 percent of new vehicle sales in 1990 to 48 percent in 2004. Starting in 2005, average new vehicle fuel economy began to increase while light-duty vehicle VMT grew only modestly for much of the period. Light-duty vehicle VMT grew by less than one percent or declined each year between 2005 and 2013,[24] then grew at a faster rate until 2016 (2.6 percent from 2014 to 2015, and 2.5 percent from 2015 to 2016). Between 2016 and 2019, the rate of light-duty VMT growth slowed to less than one percent each year. In 2020, light-duty VMT declined by 12.2 percent from 2019 to 2020 due to the COVID-19 pandemic and associated restrictions. Average new vehicle fuel economy has increased almost every year since 2005, while the light-duty truck share decreased to about 33 percent in 2009 and has since varied from year to year between 36 and 56 percent. Since 2014, the light-duty truck share has slowly increased and is about 56 percent of new vehicles sales in model year 2020 (EPA 2021b). See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles (in VMT).

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[23] Biofuel estimates are presented in the Energy chapter for informational purposes only, in line with IPCC methodological guidance and UNFCCC reporting obligations. Net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 6). More information and additional analyses on biofuels are available at EPA's Renewable Fuels Standards website. See https://www.epa.gov/renewable-fuel-standard-program.

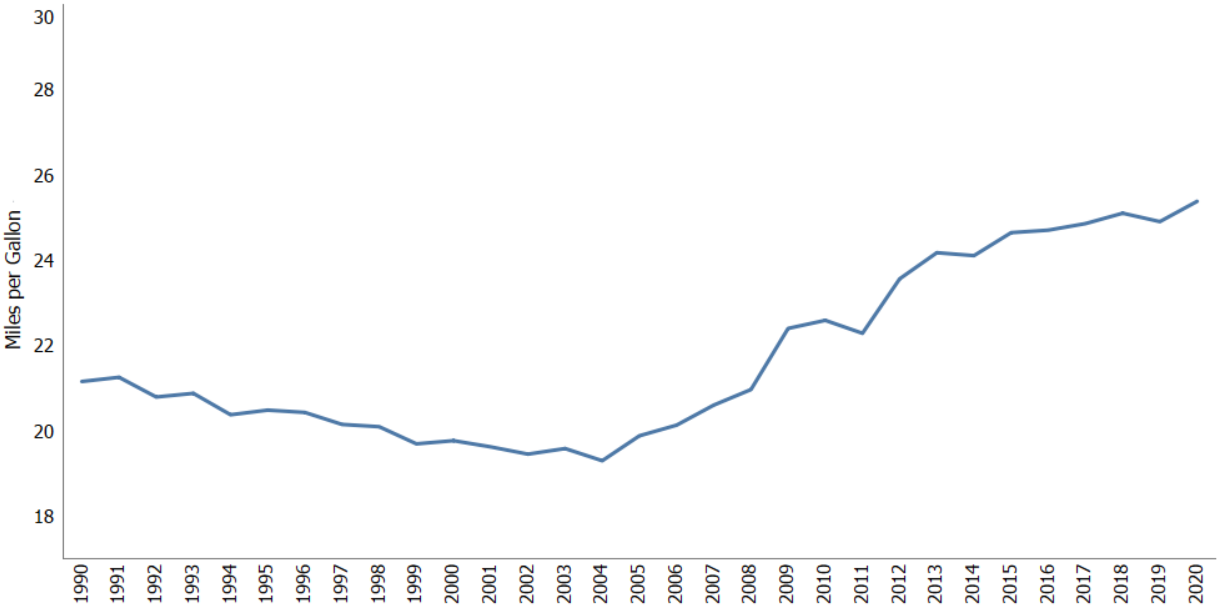
[24] VMT estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2021). In 2007 and 2008 light-duty VMT decreased 3.0 percent and 2.3 percent, respectively. Note that the decline in light-duty VMT from 2006 to 2007 is due at least in part to a change in FHWA's methods for estimating VMT. In 2011, FHWA changed its methods for estimating VMT by vehicle class, which led to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2020 time period. In absence of these method changes, light-duty VMT growth between 2006 and 2007 would likely have been higher.

Medium- and heavy-duty truck CO_2 emissions increased by 80 percent from 1990 to 2020. This increase was largely due to a substantial growth in medium- and heavy-duty truck VMT, which increased by 107 percent between 1990 and 2020.[25]

Carbon dioxide emissions from the domestic operation of commercial aircraft increased by 22 percent (24.3 MMT CO_2) from 1990 to 2019, followed by a decline of 32 percent (42.9 MMT CO_2) from 2019 to 2020. Across all categories of aviation, excluding international bunkers, CO_2 emissions decreased by 4 percent (7.8 MMT CO_2) between 1990 and 2019, followed by a sharper decline of 32 percent (57.3 MMT CO_2) between 2019 and 2020.[26] Emissions from military aircraft decreased 70 percent between 1990 and 2020. Commercial aircraft emissions increased 27 percent between 1990 and 2007, dropped 4 percent from 2007 to 2019, and then dropped 32 percent from 2019 to 2020, a change of approximately 17 percent between 1990 and 2020.

Transportation sources also produce CH_4 and N_2O; these emissions are included in Table 3-14and Table 3-15 and in the CH_4 and N_2O from Mobile Combustion section. Annex 3.2 presents total emissions from all transportation and mobile sources, including CO_2, CH_4, N_2O, and HFCs.

Figure 3-15: Sales-Weighted Fuel Economy of New Passenger Cars and Light-Duty Trucks, 1990–2020



Source: EPA (2021a).

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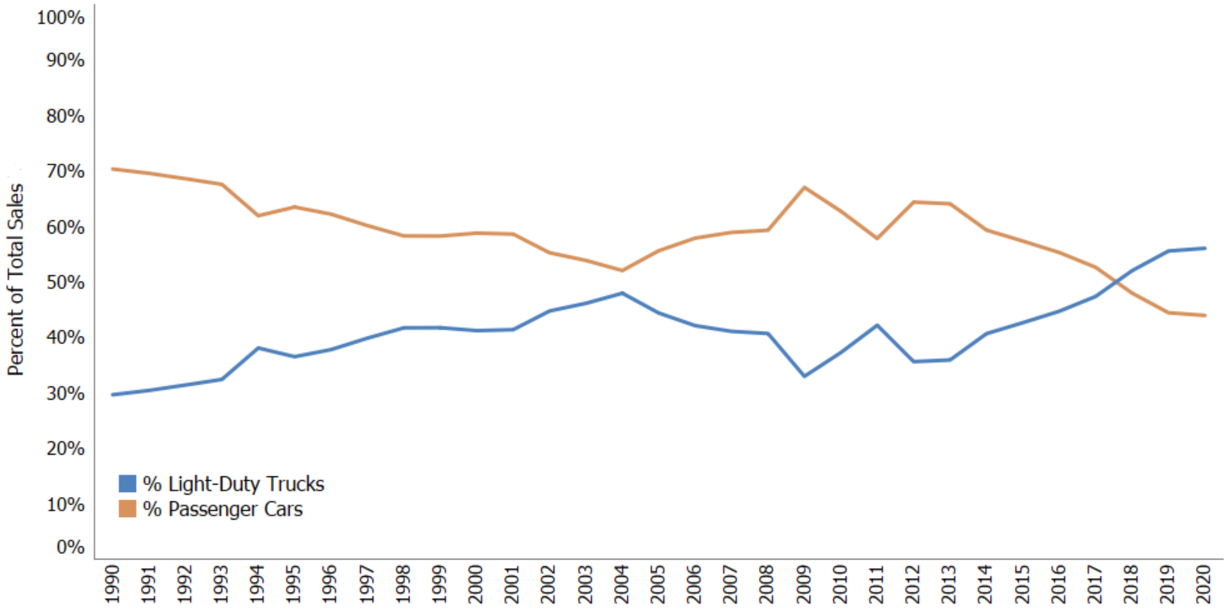
[25] While FHWA data shows consistent growth in medium- and heavy-duty truck VMT over the 1990 to 2020 time period, part of the growth reflects a method change for estimating VMT starting in 2007. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class, thus leading to a shift in VMT and emissions among on-road vehicle classes in the 2007 to 2020 time period. During the time period prior to the method change (1990 to 2006), VMT for medium- and heavy-duty trucks increased by 51 percent.

[26] Includes consumption of jet fuel and aviation gasoline. Does not include aircraft bunkers, which are not included in national emission totals, in line with IPCC methodological guidance and UNFCCC reporting obligations.

Figure 3-16: Sales of New Passenger Cars and Light-Duty Trucks, 1990–2020



Source: EPA (2021b).

Table 3-13: CO$_2$ Emissions from Fossil Fuel Combustion in Transportation End-Use Sector (MMT CO$_2$ Eq.)

Fuel/Vehicle Type	1990	2005	2016[a]	2017[a]	2018[a]	2019[a]	2020[a]
Gasoline[b]	**958.9**	**1,150.1**	**1,084.4**	**1,081.8**	**1,097.0**	**1,086.5**	**936.9**
Passenger Cars	604.3	637.1	737.5	737.4	748.7	742.1	599.9
Light-Duty Trucks	300.6	463.5	291.7	288.2	290.9	289.0	283.4
Medium- and Heavy-Duty Trucks[c]	37.7	33.8	40.0	40.9	41.9	40.1	39.6
Buses	0.3	0.4	0.9	0.9	1.0	1.0	0.8
Motorcycles	1.7	1.6	3.8	3.7	3.8	3.6	3.2
Recreational Boats[d]	14.3	13.7	10.6	10.6	10.7	10.7	9.9
Distillate Fuel Oil (Diesel)[b]	**274.6**	**472.1**	**461.1**	**474.9**	**486.6**	**484.1**	**455.0**
Passenger Cars	7.9	4.3	4.2	4.3	4.3	4.5	3.5
Light-Duty Trucks	11.5	26.1	14.0	14.0	14.1	14.7	13.9
Medium- and Heavy-Duty Trucks[c]	190.5	364.2	367.9	379.6	388.5	389.5	372.9
Buses	8.0	10.7	16.6	17.8	19.0	19.0	15.5
Rail	35.5	46.1	36.1	37.4	38.5	36.0	31.0
Recreational Boats[d]	2.7	2.9	2.7	2.8	2.8	2.9	2.6
Ships and Non-Recreational Boats[e]	6.8	8.4	10.9	10.0	9.3	7.5	7.6
International Bunker Fuels[f]	*11.7*	*9.5*	*8.7*	*9.0*	*10.0*	*10.1*	*7.8*
Jet Fuel	**222.3**	**249.5**	**240.1**	**249.4**	**253.1**	**258.5**	**160.4**
Commercial Aircraft[g]	109.9	132.7	120.4	128.0	129.6	134.2	91.3
Military Aircraft	35.7	19.8	12.5	12.5	12.1	12.1	10.7
General Aviation Aircraft	38.5	36.8	33.0	31.2	30.6	31.4	18.6
International Bunker Fuels[f]	*38.2*	*60.2*	74.1	77.8	80.9	80.8	39.8
International Bunker Fuels from Commercial Aviation	*30.0*	*55.6*	*70.8*	*74.5*	*77.7*	*77.6*	*36.7*
Aviation Gasoline	**3.1**	**2.4**	**1.4**	**1.4**	**1.5**	**1.6**	**1.4**
General Aviation Aircraft	3.1	2.4	1.4	1.4	1.5	1.6	1.4

Residual Fuel Oil	**76.3**	**62.9**	**46.8**	**49.9**	**45.4**	**39.7**	**29.6**
Ships and Non-Recreational Boats[e]	22.6	19.3	12.9	16.5	14.0	14.5	7.5
International Bunker Fuels[f]	*53.7*	*43.6*	33.8	33.4	31.4	25.2	22.1
Natural Gas[j]	**36.0**	**33.1**	**40.1**	**42.3**	**50.9**	**58.9**	**58.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+
Buses	+	0.6	0.8	0.9	0.9	1.0	0.9
Pipeline[h]	36.0	32.4	39.2	41.3	49.9	57.9	57.1
LPG[j]	**1.4**	**1.8**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	0.2	0.3	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Trucks[c]	1.1	1.3	0.3	0.3	0.3	0.3	0.3
Buses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Electricity[l]	**3.0**	**4.7**	**4.2**	**4.3**	**4.7**	**4.7**	**4.7**
Passenger Cars	+	+	0.6	0.8	1.2	1.4	1.6
Light-Duty Trucks	+	+	0.1	0.1	0.2	0.2	0.4
Buses	+	+	+	+	+	+	+
Rail	3.0	4.7	3.5	3.4	3.3	3.1	2.6
Total (Excluding Bunkers)[f]	**1,472.0**	**1,863.3**	**1,761.8**	**1,784.3**	**1,817.4**	**1,818.5**	**1,576.7**
Total (Including Bunkers)[k]	**1,575.6**	**1,976.6**	**1,878.5**	**1,904.5**	**1,939.6**	**1,934.6**	**1,646.3**
Biofuels-Ethanol[i]	*4.1*	*21.6*	*76.9*	*77.7*	*78.6*	*78.7*	*68.1*
Biofuels-Biodiesel[i]	*+*	*0.9*	*19.6*	*18.7*	*17.9*	*17.1*	*17.7*

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2020 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[b] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-27 and VM-1 (FHWA 1996 through 2021). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2021).

[c] Includes medium- and heavy-duty trucks over 8,500 lbs.

[d] In 2014, EPA incorporated the NONROAD2008 model into the MOVES model framework. The current Inventory uses the Nonroad component of MOVES3 for years 1999 through 2020.

[e] Note that large year over year fluctuations in emission estimates partially reflect nature of data collection for these sources.

[f] Official estimates exclude emissions from the combustion of both aviation and marine international bunker fuels; however, estimates including international bunker fuel-related emissions are presented for informational purposes.

[g] Commercial aircraft, as modeled in FAA's Aviation Environmental Design Tool (AEDT), consists of passenger aircraft, cargo, and other chartered flights.

[h] Pipelines reflect CO_2 emissions from natural gas-powered pipelines transporting natural gas.

[i] Ethanol and biodiesel estimates are presented for informational purposes only. See Section 3.10 of this chapter and the estimates in Land Use, Land-Use Change, and Forestry (see Chapter 6), in line with IPCC methodological guidance and UNFCCC reporting obligations, for more information on ethanol and biodiesel.

[j] Transportation sector natural gas and LPG consumption are based on data from EIA (2021b). Prior to the 1990 to 2015 Inventory, data from DOE TEDB were used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 to 2016 Inventory and apply to the 1990 to 2020 time period.

[k] Includes emissions from rail electricity.

[l] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales and engine efficiency data, as outlined in Browning (2018a). In prior Inventory years, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes apply to the 2010 through 2020 time period.

Notes: This table does not include emissions from non-transportation mobile sources, such as agricultural equipment and construction/mining equipment; it also does not include emissions associated with electricity consumption by pipelines or lubricants used in transportation. In addition, this table does not include CO_2 emissions from U.S. Territories, since these are covered in a separate chapter of the Inventory. Totals may not sum due to independent rounding.

Mobile Fossil Fuel Combustion CH_4 and N_2O Emissions

Mobile combustion includes emissions of CH_4 and N_2O from all transportation sources identified in the U.S. Inventory with the exception of pipelines and electric locomotives;[27] mobile sources also include non-transportation sources such as construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources (e.g., snowmobiles, lawnmowers, etc.).[28] Annex 3.2 includes a summary of all emissions from both transportation and mobile sources. Table 3-14 and Table 3-15 provide mobile fossil fuel CH_4 and N_2O emission estimates in MMT CO_2 Eq.[29]

Mobile combustion was responsible for a small portion of national CH_4 emissions (0.3 percent) and was the fifth largest source of national N_2O emissions (4.1 percent). From 1990 to 2020, mobile source CH_4 emissions declined by 66 percent, to 2.2 MMT CO_2 Eq. (88 kt CH_4), due largely to emissions control technologies employed in on-road vehicles since the mid-1990s to reduce CO, NO_x, NMVOC, and CH_4 emissions. Mobile source emissions of N_2O decreased by 61 percent from 1990 to 2020, to 17.4 MMT CO_2 Eq. (58 kt N_2O). Earlier generation emissions control technologies initially resulted in higher N_2O emissions, causing a 29 percent increase in N_2O emissions from mobile sources between 1990 and 1997. Improvements in later-generation emissions control technologies have reduced N_2O emissions, resulting in a 70 percent decrease in mobile source N_2O emissions from 1997 to 2020 (Figure 3-17). Overall, CH_4 and N_2O emissions were predominantly from gasoline-fueled passenger cars and light-duty trucks and non-highway sources. See Annex 3.2 for data by vehicle mode and information on VMT and the share of new vehicles.

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[27] Emissions of CH_4 from natural gas systems are reported separately. More information on the methodology used to calculate these emissions are included in this chapter and Annex 3.4.

[28] See the methodology sub-sections of the CO_2 from Fossil Fuel Combustion and CH_4 and N_2O from Mobile Combustion sections of this chapter. Note that N_2O and CH_4 emissions are reported using different categories than CO_2. CO_2 emissions are reported by end-use sector (Transportation, Industrial, Commercial, Residential, U.S. Territories), and generally adhere to a top-down approach to estimating emissions. CO_2 emissions from non-transportation sources (e.g., lawn and garden equipment, farm equipment, construction equipment) are allocated to their respective end-use sector (i.e., construction equipment CO_2 emissions are included in the Industrial end-use sector instead of the Transportation end-use sector). CH_4 and N_2O emissions are reported using the "Mobile Combustion" category, which includes non-transportation mobile sources. CH_4 and N_2O emission estimates are bottom-up estimates, based on total activity (fuel use, VMT) and emissions factors by source and technology type. These reporting schemes are in accordance with IPCC guidance. For informational purposes only, CO_2 emissions from non-transportation mobile sources are presented separately from their overall end-use sector in Annex 3.2.

[29] See Annex 3.2 for a complete time series of emission estimates for 1990 through 2020.

Figure 3-17: Mobile Source CH_4 and N_2O Emissions

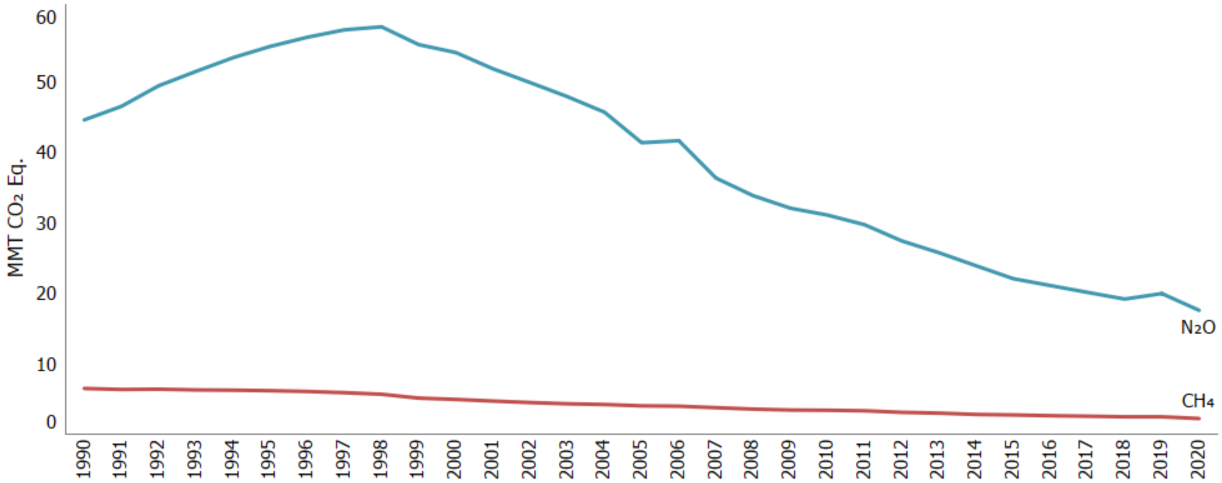

Table 3-14: CH_4 Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2016	2017	2018	2019	2020
Gasoline On-Road[b]	**5.2**	**2.2**	**0.9**	**0.8**	**0.7**	**0.8**	**0.6**
Passenger Cars	3.2	1.3	0.6	0.5	0.5	0.5	0.4
Light-Duty Trucks	1.7	0.8	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks and Buses	0.3	0.1	+	+	+	+	+
Motorcycles	+	+	+	+	+	+	+
Diesel On-Road[b]	**+**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Passenger Cars	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Buses	+	+	+	+	+	+	+
Alternative Fuel On-Road	**+**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**+**
Non-Road[g]	**1.3**	**1.6**	**1.5**	**1.6**	**1.6**	**1.5**	**1.4**
Ships and Boats	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Rail [c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aircraft	0.1	0.1	+	+	+	+	+
Agricultural Equipment[d]	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Construction/Mining Equipment[e]	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Other[f]	0.5	0.7	0.7	0.7	0.7	0.7	0.7
Total	**6.5**	**4.0**	**2.6**	**2.6**	**2.5**	**2.5**	**2.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1.

[c] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 to 2017 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

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[g] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7% reduction factor is used, based on transportation diesel use (EIA 2022).

Notes: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2020 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.

Table 3-15: N_2O Emissions from Mobile Combustion (MMT CO_2 Eq.)

Fuel Type/Vehicle Type[a]	1990	2005	2016	2017	2018	2019	2020
Gasoline On-Road[b]	**37.5**	**31.9**	**10.2**	**8.7**	**7.3**	**7.9**	**6.2**
Passenger Cars	24.1	17.3	7.0	6.0	5.1	5.2	3.9
Light-Duty Trucks	12.8	13.6	2.7	2.3	1.9	2.4	2.1
Medium- and Heavy-Duty Trucks and Buses	0.5	0.9	0.3	0.3	0.2	0.2	0.2
Motorcycles	+	+	0.1	0.1	0.1	0.1	0.1
Diesel On-Road[b]	**0.2**	**0.3**	**2.7**	**3.0**	**3.3**	**3.3**	**3.4**
Passenger Cars	+	+	0.1	0.1	0.1	0.1	+
Light-Duty Trucks	+	+	0.1	0.1	0.1	0.1	0.1
Medium- and Heavy-Duty Trucks	0.2	0.3	2.3	2.5	2.8	2.8	3.0
Medium- and Heavy-Duty Buses	+	+	0.3	0.3	0.3	0.3	0.3
Alternative Fuel On-Road	**+**	**+**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Non-Road[g]	**6.9**	**9.2**	**8.0**	**8.3**	**8.4**	**8.5**	**7.6**
Ships and Boats	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Rail[c]	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Aircraft	1.7	1.7	1.5	1.6	1.6	1.6	1.1
Agricultural Equipment[d]	1.4	1.6	1.3	1.2	1.2	1.2	1.2
Construction/Mining Equipment[e]	1.3	2.1	1.6	1.8	1.8	1.9	1.8
Other[f]	2.0	3.1	3.1	3.2	3.2	3.3	3.1
Total	**44.6**	**41.3**	**21.1**	**20.1**	**19.2**	**20.0**	**17.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] See Annex 3.2 for definitions of on-road vehicle types.

[b] Gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1.

[c] Rail emissions do not include emissions from electric powered locomotives. Class II and Class III diesel consumption data for 2014 through 2017 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

[g] Nonroad fuel consumption estimates for 2020 are adjusted to account for the COVID-19 pandemic and associated restrictions. For agricultural equipment and airport equipment, sector specific adjustment factors were applied to the 2019 data. For all other sectors, a 7.7 percent reduction factor is used, based on transportation diesel use (EIA 2022).

Notes: In 2011, FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2020 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. Totals may not sum due to independent rounding.

CO_2 from Fossil Fuel Combustion

Methodology and Time-Series Consistency

CO_2 emissions from fossil fuel combustion are estimated in line with a Tier 2 method described by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) with some exceptions as discussed below.[30] A detailed description of the U.S. methodology is presented in Annex 2.1, and is characterized by the following steps:

1. *Determine total fuel consumption by fuel type and sector*. Total fossil fuel consumption for each year is estimated by aggregating consumption data by end-use sector (e.g., commercial, industrial), primary fuel type (e.g., coal, petroleum, gas), and secondary fuel category (e.g., motor gasoline, distillate fuel oil). Fuel consumption data for the United States were obtained directly from the EIA of the U.S. Department of Energy (DOE), primarily from the *Monthly Energy Review* (EIA 2022a). EIA data include fuel consumption statistics from the 50 U.S. states and the District of Columbia, including tribal lands. The EIA does not include territories in its national energy statistics, so fuel consumption data for territories were collected separately from EIA's International Energy Statistics (EIA 2022b).[31]

   For consistency of reporting, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention and/or IEA data. Data in the IEA format are presented "top down"—that is, energy consumption for fuel types and categories are estimated from energy production data (accounting for imports, exports, stock changes, and losses). The resulting quantities are referred to as "apparent consumption." The data collected in the United States by EIA on an annual basis and used in this Inventory are predominantly from mid-stream or conversion energy consumers such as refiners and electric power generators. These annual surveys are supplemented with end-use energy consumption surveys, such as the Manufacturing Energy Consumption Survey, that are conducted on a periodic basis (every four years). These consumption datasets help inform the annual surveys to arrive at the national total and sectoral breakdowns for that total.[32]

   Also, note that U.S. fossil fuel energy statistics are generally presented using gross calorific values (GCV) (i.e., higher heating values). Fuel consumption activity data presented here have not been adjusted to correspond to international standards, which are to report energy statistics in terms of net calorific values (NCV) (i.e., lower heating values).[33]

   Subtract uses accounted for in the Industrial Processes and Product Use chapter. Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—were reallocated to the Industrial Processes and Product Use chapter, as they were consumed during non-energy-related industrial activity. To make these adjustments, additional data were collected from AISI (2004 through 2021), Coffeyville (2012), U.S. Census Bureau (2001 through 2011), EIA (2022a, 2021b, 2021e), USAA (2008 through 2021), USGS (1991 through 2020), (USGS 2019), USGS (2014 through 2021a), USGS (2014 through 2021b), USGS (1995 through 2013), USGS (1995, 1998, 2000, 2001, 2002, 2007), USGS (2021a), USGS (1991 through 2015a), USGS (1991

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[30] The IPCC Tier 3B methodology is used for estimating emissions from commercial aircraft.

[31] Fuel consumption by U.S. Territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report and contributed total emissions of 22.7 MMT CO_2 Eq. in 2020. Data is only available for EIA's International Energy Statistics through 2020 for coal and natural gas consumption and through 2019 for petroleum consumption. For this reason, data for the 2020 U.S. Territories emission estimates is proxied to the most recent data available.

[32] See IPCC Reference Approach for Estimating CO_2 Emissions from Fossil Fuel Combustion in Annex 4 for a comparison of U.S. estimates using top-down and bottom-up approaches.

[33] A crude convention to convert between gross and net calorific values is to multiply the heat content of solid and liquid fossil fuels by 0.95 and gaseous fuels by 0.9 to account for the water content of the fuels. Biomass-based fuels in U.S. energy statistics, however, are generally presented using net calorific values.

through 2020), USGS (2014 through 2021a), USGS (1991 through 2015b), USGS (2021b), USGS (1991 through 2020).[34]

2. *Adjust for biofuels and petroleum denaturant*. Fossil fuel consumption estimates are adjusted downward to exclude fuels with biogenic origins and avoid double counting in petroleum data statistics. Carbon dioxide emissions from ethanol added to motor gasoline and biodiesel added to diesel fuel are not included specifically in summing energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF, therefore, fuel consumption estimates are adjusted to remove ethanol and biodiesel.[35] For the years 1993 through 2008, petroleum denaturant is currently included in EIA statistics for both natural gasoline and finished motor gasoline. To avoid double counting, petroleum denaturant is subtracted from finished motor gasoline for these years.[36]

3. *Adjust for exports of CO_2.* Since October 2000, the Dakota Gasification Plant has been exporting CO_2 produced in the coal gasification process to Canada by pipeline. Because this CO_2 is not emitted to the atmosphere in the United States, the associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 is subtracted from EIA (2021e) coal consumption statistics that are used to calculate greenhouse gas emissions from the Energy Sector. The associated fossil fuel is the total fossil fuel burned at the plant with the CO_2 capture system multiplied by the fraction of the plant's total site-generated CO_2 that is recovered by the capture system. To make these adjustments, data for CO_2 exports were collected from Environment and Climate Change Canada (2022). A discussion of the methodology used to estimate the amount of CO_2 captured and exported by pipeline is presented in Annex 2.1.

4. *Adjust sectoral allocation of distillate fuel oil and motor gasoline.* EPA conducted a separate bottom-up analysis of transportation fuel consumption based on data from the Federal Highway Administration that indicated that the amount of distillate and motor gasoline consumption allocated to the transportation sector in the EIA statistics should be adjusted. Therefore, for these estimates, the transportation sector's distillate fuel and motor gasoline consumption were adjusted to match the value obtained from the bottom-up analysis. As the total distillate and motor gasoline consumption estimate from EIA are considered to be accurate at the national level, the distillate and motor gasoline consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately. The data sources used in the bottom-up analysis of transportation fuel consumption include AAR (2008 through 2020), Benson (2002 through 2004), DOE (1993 through 2017), EIA (2007), EIA (1991 through 2020), EPA (2021b), and FHWA (1996 through 2021).[37]

5. *Adjust for fuels consumed for non-energy uses*. U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. These are fossil fuels that are manufactured into plastics, asphalt, lubricants, or other products. Depending on the end-use, this can result in storage of some or all of the C contained in the fuel for a period of time. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion (since the C in these fuels ends up in products instead of being combusted), these emissions are estimated separately in Section 3.2 – Carbon Emitted and Stored in Products from Non-Energy Uses of Fossil Fuels. Therefore, the amount of fuels used for non-energy purposes was subtracted from total fuel consumption. Data on non-fuel consumption were provided by EIA (2021b).

6. *Subtract consumption of international bunker fuels.* According to the UNFCCC reporting guidelines emissions from international transport activities, or bunker fuels, should not be included in national

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[34] See sections on Iron and Steel Production and Metallurgical Coke Production, Ammonia Production and Urea Consumption, Petrochemical Production, Titanium Dioxide Production, Ferroalloy Production, Aluminum Production, and Silicon Carbide Production and Consumption in the Industrial Processes and Product Use chapter.

[35] Natural gas energy statistics from EIA (2021d) are already adjusted downward to account for biogas in natural gas.

[36] These adjustments are explained in greater detail in Annex 2.1.

[37] Bottom-up gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2021).

totals. U.S. energy consumption statistics include these bunker fuels (e.g., distillate fuel oil, residual fuel oil, and jet fuel) as part of consumption by the transportation end-use sector, however, so emissions from international transport activities were calculated separately following the same procedures used to calculate emissions from consumption of all fossil fuels (i.e., estimation of consumption, and determination of Carbon content).[38] The Office of the Under Secretary of Defense (Installations and Environment) and the Defense Logistics Agency Energy (DLA Energy) of the U.S. Department of Defense (DoD) (DLA Energy 2021) supplied data on military jet fuel and marine fuel use. Commercial jet fuel use was estimated based on data from FAA (2022) and DOT (1991 through 2020); residual and distillate fuel use for civilian marine bunkers was obtained from DOC (1991 through 2020) for 1990 through 2001 and 2007 through 2020, and DHS (2008) for 2003 through 2006.[39] Consumption of these fuels was subtracted from the corresponding fuels totals in the transportation end-use sector. Estimates of international bunker fuel emissions for the United States are discussed in detail in Section 3.9 – International Bunker Fuels.

7. *Determine the total Carbon content of fuels consumed.* Total C was estimated by multiplying the amount of fuel consumed by the amount of C in each fuel. This total C estimate defines the maximum amount of C that could potentially be released to the atmosphere if all of the C in each fuel was converted to CO_2. A discussion of the methodology and sources used to develop the C content coefficients are presented in Annexes 2.1 and 2.2.

8. *Estimate CO_2 Emissions.* Total CO_2 emissions are the product of the adjusted energy consumption (from the previous methodology steps 1 through 6), the Carbon content of the fuels consumed, and the fraction of C that is oxidized. The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Annex 2.1). Carbon emissions were multiplied by the molecular-to-atomic weight ratio of CO_2 to C (44/12) to obtain total CO_2 emitted from fossil fuel combustion in million metric tons (MMT).

9. *Allocate transportation emissions by vehicle type.* This report provides a more detailed accounting of emissions from transportation because it is such a large consumer of fossil fuels in the United States. For fuel types other than jet fuel, fuel consumption data by vehicle type and transportation mode were used to allocate emissions by fuel type calculated for the transportation end-use sector. Heat contents and densities were obtained from EIA (2021b) and USAF (1998).[40]

    - For on-road vehicles, annual estimates of combined motor gasoline and diesel fuel consumption by vehicle category were obtained from FHWA (1996 through 2021); for each vehicle category, the

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[38] See International Bunker Fuels section in this chapter for a more detailed discussion.

[39] Data for 2002 were interpolated due to inconsistencies in reported fuel consumption data.

[40] For a more detailed description of the data sources used for the analysis of the transportation end use sector see the Mobile Combustion (excluding CO_2) and International Bunker Fuels sections of the Energy chapter, Annex 3.2, and Annex 3.8, respectively.

percent gasoline, diesel, and other (e.g., CNG, LPG) fuel consumption are estimated using data from DOE (1993 through 2021). [41,42]

- For non-road vehicles, activity data were obtained from AAR (2008 through 2021), APTA (2007 through 2021), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), DLA Energy (2021), DOC (1991 through 2020), DOE (1993 through 2021), DOT (1991 through 2021), EIA (2009a), EIA (2021d), EIA (2002), EIA (1991 through 2020), EPA (2021b),[43] and Gaffney (2007).
- For jet fuel used by aircraft, CO_2 emissions from commercial aircraft were developed by the U.S. Federal Aviation Administration (FAA) using a Tier 3B methodology, consistent IPCC (2006) (see Annex 3.3). Carbon dioxide emissions from other aircraft were calculated directly based on reported consumption of fuel as reported by EIA. Allocation to domestic military uses was made using DoD data (see Annex 3.8). General aviation jet fuel consumption is calculated as the remainder of total jet fuel use (as determined by EIA) nets all other jet fuel use as determined by FAA and DoD. For more information, see Annex 3.2.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. Due to data availability and sources, some adjustments outlined in the methodology above are not applied consistently across the full 1990 to 2020 time series. As described in greater detail in Annex 2.1, to align with EIA's methodology for calculating motor gasoline consumption, petroleum denaturant adjustments are applied to motor gasoline consumption only for the period 1993 through 2008. In addition to ensuring time-series consistency, to ensure consistency in reporting between the Inventory and the Canadian National Greenhouse Gas Inventory, the amount of associated fossil fuel (lignite coal) that is gasified to create the exported CO_2 from the Dakota Gasification Plant is adjusted to align with the Canadian National Greenhouse Gas Inventory (Environment and Climate Change Canada 2022). This adjustment is explained in greater detail in Annex 2.1. As discussed in Annex 5, data are unavailable to include estimates of CO_2 emissions from any liquid fuel used in pipeline transport or non-hazardous industrial waste incineration, but those emissions are assumed to be insignificant.

Box 3-4: Carbon Intensity of U.S. Energy Consumption

The amount of C emitted from the combustion of fossil fuels is dependent upon the carbon content of the fuel and the fraction of that C that is oxidized. Fossil fuels vary in their average carbon content, ranging from about 53 MMT CO_2 Eq./QBtu for natural gas to upwards of 95 MMT CO_2 Eq./QBtu for coal and petroleum coke (see Tables A-42 and A-43 in Annex 2.1 for carbon contents of all fuels). In general, the carbon content per unit of energy of fossil fuels is the highest for coal products, followed by petroleum, and then natural gas. The overall carbon intensity of the U.S. economy is thus dependent upon the quantity and combination of fuels and other energy sources employed to meet demand.

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[41] Data from FHWA's Table VM-1 is used to estimate the share of fuel consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2021). In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the time period from 2007 through 2020. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes.

[42] Transportation sector natural gas and LPG consumption are based on data from EIA (2020g). In previous Inventory years, data from DOE (1993 through 2021) TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium- and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in the 1990 through 2015 Inventory and apply to the time period from 1990 to 2015.

[43] In 2014, EPA incorporated the NONROAD2008 model into MOVES2014 (EPA 2019). In 2021, EPA updated the MOVESV model to MOVES3 (EPA 2021b). The current Inventory uses the Nonroad component of MOVES2014b for years 1999 through 2020.

Table 3-16 provides a time series of the carbon intensity of direct emissions for each sector of the U.S. economy. The time series incorporates only the energy from the direct combustion of fossil fuels in each sector. For example, the carbon intensity for the residential sector does not include the energy from or emissions related to the use of electricity for lighting, as it is instead allocated to the electric power sector. For the purposes of maintaining the focus of this section, renewable energy and nuclear energy are not included in the energy totals used in Table 3-16 in order to focus attention on fossil fuel combustion as detailed in this chapter. Looking only at this direct consumption of fossil fuels, the residential sector exhibited the lowest carbon intensity, which is related to the large percentage of its energy derived from natural gas for heating. The carbon intensity of the commercial sector has predominantly declined since 1990 as commercial businesses shift away from petroleum to natural gas. The industrial sector was more dependent on petroleum and coal than either the residential or commercial sectors, and thus had higher C intensities over this period. The Carbon intensity of the transportation sector was closely related to the Carbon content of petroleum products (e.g., motor gasoline and jet fuel, both around 70 MMT CO_2 Eq./QBtu), which were the primary sources of energy. Lastly, the electric power sector had the highest Carbon intensity due to its heavy reliance on coal for generating electricity.

Table 3-16: Carbon Intensity from Direct Fossil Fuel Combustion by Sector (MMT CO_2 Eq./QBtu)

Sector	1990	2005	2016	2017	2018	2019	2020
Residential[a]	57.4	56.8	55.2	55.1	55.3	55.2	55.1
Commercial[a]	59.7	57.8	56.7	56.6	56.0	56.1	56.2
Industrial[a]	64.5	64.6	61.1	60.8	60.5	60.3	59.8
Transportation[a]	71.1	71.5	71.1	71.2	71.0	70.9	70.9
Electric Power[b]	87.3	85.8	76.8	77.3	75.5	72.9	70.5
U.S. Territories[c]	72.3	72.6	71.0	71.1	70.5	70.9	71.8
All Sectors[c]	**73.1**	**73.6**	**69.2**	**69.1**	**68.3**	**67.3**	**66.3**

[a] Does not include electricity or renewable energy consumption.

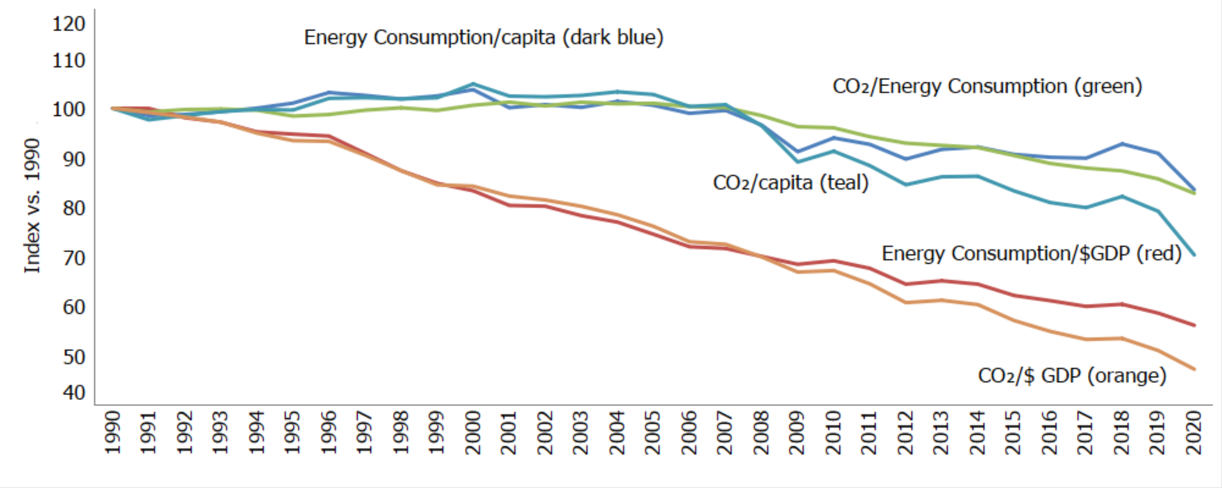
[b] Does not include electricity produced using nuclear or renewable energy.

[c] Does not include nuclear or renewable energy consumption.

Note: Excludes non-energy fuel use emissions and consumption.

For the time period of 1990 through about 2008, the carbon intensity of U.S. energy consumption was fairly constant, as the proportion of fossil fuels used by the individual sectors did not change significantly over that time. Starting in 2008 the carbon intensity has decreased, reflecting the shift from coal to natural gas in the electric power sector during that time period. Per capita energy consumption fluctuated little from 1990 to 2007, but then started decreasing after 2007 and, in 2020, was approximately 16.5 percent below levels in 1990 (see Figure 3-18). To differentiate these estimates from those of Table 3-16, the carbon intensity trend shown in Figure 3-18 and described below includes nuclear and renewable energy EIA data to provide a comprehensive economy-wide picture of energy consumption. Due to a general shift from a manufacturing-based economy to a service-based economy, as well as overall increases in efficiency, energy consumption and energy-related CO_2 emissions per dollar of gross domestic product (GDP) have both declined since 1990 (BEA 2022).

Figure 3-18: U.S. Energy Consumption and Energy-Related CO_2 Emissions Per Capita and Per Dollar GDP



Carbon intensity estimates were developed using nuclear and renewable energy data from EIA (2021b), EPA (2010), and fossil fuel consumption data as discussed above and presented in Annex 2.1.

Uncertainty

For estimates of CO_2 from fossil fuel combustion, the amount of CO_2 emitted is directly related to the amount of fuel consumed, the fraction of the fuel that is oxidized, and the carbon content of the fuel. Therefore, a careful accounting of fossil fuel consumption by fuel type, average carbon contents of fossil fuels consumed, and production of fossil fuel-based products with long-term carbon storage should yield an accurate estimate of CO_2 emissions.

Nevertheless, there are uncertainties in the consumption data, carbon content of fuels and products, and carbon oxidation efficiencies. For example, given the same primary fuel type (e.g., coal, petroleum, or natural gas), the amount of carbon contained in the fuel per unit of useful energy can vary. For the United States, however, the impact of these uncertainties on overall CO_2 emission estimates is believed to be relatively small. See, for example, Marland and Pippin (1990). See also Annex 2.2 for a discussion of uncertainties associated with fuel carbon contents. Recent updates to carbon factors for natural gas and coal utilized the same approach as previous Inventories with updated recent data, therefore, the uncertainty estimates around carbon contents of the different fuels as outlined in Annex 2.2 were not impacted and the historic uncertainty ranges still apply.

Although national statistics of total fossil fuel and other energy consumption are relatively accurate, the allocation of this consumption to individual end-use sectors (i.e., residential, commercial, industrial, and transportation) is less certain. For example, for some fuels the sectoral allocations are based on price rates (i.e., tariffs), but a commercial establishment may be able to negotiate an industrial rate or a small industrial establishment may end up paying an industrial rate, leading to a misallocation of emissions. Also, the deregulation of the natural gas industry and the more recent deregulation of the electric power industry have likely led to some minor challenges in collecting accurate energy statistics as firms in these industries have undergone significant restructuring.

To calculate the total CO_2 emission estimate from energy-related fossil fuel combustion, the amount of fuel used in non-energy production processes were subtracted from the total fossil fuel consumption. The amount of CO_2 emissions resulting from non-energy related fossil fuel use has been calculated separately and reported in the Carbon Emitted from Non-Energy Uses of Fossil Fuels section of this report (Section 3.2). These factors all contribute to the uncertainty in the CO_2 estimates. Detailed discussions on the uncertainties associated with C emitted from Non-Energy Uses of Fossil Fuels can be found within that section of this chapter.

Various sources of uncertainty surround the estimation of emissions from international bunker fuels, which are subtracted from the U.S. totals (see the detailed discussions on these uncertainties provided in Section 3.9 – International Bunker Fuels). Another source of uncertainty is fuel consumption by U.S. Territories. The United States does not collect energy statistics for its territories at the same level of detail as for the fifty states and the District of Columbia. Therefore, estimating both emissions and bunker fuel consumption by these territories is difficult.

Uncertainties in the emission estimates presented above also result from the data used to allocate CO_2 emissions from the transportation end-use sector to individual vehicle types and transport modes. In many cases, bottom-up estimates of fuel consumption by vehicle type do not match aggregate fuel-type estimates from EIA. Further research is planned to improve the allocation into detailed transportation end-use sector emissions.

The uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software. For this uncertainty estimation, the inventory estimation model for CO_2 from fossil fuel combustion was integrated with the relevant variables from the inventory estimation model for International Bunker Fuels, to realistically characterize the interaction (or endogenous correlation) between the variables of these two models. About 170 input variables were modeled for CO_2 from energy-related Fossil Fuel Combustion (including about 20 for non-energy fuel consumption and about 20 for International Bunker Fuels).

In developing the uncertainty estimation model, uniform distributions were assumed for all activity-related input variables and emission factors, based on the SAIC/EIA (2001) report.[44] Triangular distributions were assigned for the oxidization factors (or combustion efficiencies). The uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001) and on conversations with various agency personnel.[45]

The uncertainty ranges for the activity-related input variables were typically asymmetric around their inventory estimates; the uncertainty ranges for the emissions factors were symmetric. Bias (or systematic uncertainties) associated with these variables accounted for much of the uncertainties associated with these variables (SAIC/EIA 2001).[46] For purposes of this uncertainty analysis, each input variable was simulated 10,000 times through Monte Carlo sampling.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-17. Fossil fuel combustion CO_2 emissions in 2020 were estimated to be between 4,255.1 and 4,532.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 2 percent below to 4 percent above the 2020 emission estimate of 4,342.7 MMT CO_2 Eq.

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[44] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[45] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[46] Although, in general, random uncertainties are the main focus of statistical uncertainty analysis, when the uncertainty estimates are elicited from experts, their estimates include both random and systematic uncertainties. Hence, both these types of uncertainties are represented in this uncertainty analysis.

Table 3-17: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Energy-Related Fossil Fuel Combustion by Fuel Type and Sector (MMT CO_2 Eq. and Percent)

Fuel/Sector	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal[b]	**835.6**	**807.2**	**913.7**	**-3%**	**9%**
Residential	NO	NO	NO	NO	NO
Commercial	1.4	1.3	1.6	-5%	15%
Industrial	43.0	40.9	49.8	-5%	16%
Transportation	NO	NO	NO	NO	NO
Electric Power	788.2	757.8	863.5	-4%	10%
U.S. Territories	3.1	2.7	3.7	-12%	19%
Natural Gas[b]	**1,610.7**	**1,590.7**	**1,684.1**	**-1%**	**5%**
Residential	256.4	249.0	274.4	-3%	7%
Commercial	173.9	169.0	186.1	-3%	7%
Industrial	485.5	469.6	521.3	-3%	7%
Transportation	58.1	56.4	62.1	-3%	7%
Electric Power	634.3	615.9	666.8	-3%	5%
U.S. Territories	2.6	2.3	3.1	-12%	17%
Petroleum[b]	**1,895.9**	**1,781.5**	**2,010.4**	**-6%**	**6%**
Residential	59.5	56.1	62.8	-6%	6%
Commercial	51.6	48.8	54.3	-5%	5%
Industrial	237.8	187.0	288.5	-21%	21%
Transportation	1,514.0	1,417.3	1,611.5	-6%	6%
Electric Power	16.2	15.3	17.6	-5%	9%
U.S. Territories	16.9	15.7	18.8	-7%	11%
Total (excluding Geothermal)[b]	**4,342.3**	**4,254.5**	**4,531.5**	**-2%**	**4%**
Geothermal	**0.4**	**NE**	**NE**	**NE**	**NE**
Electric Power	**0.4**	NE	NE	NE	NE
Total (including Geothermal)[b,c]	**4,342.7**	**4,255.1**	**4,532.1**	**-2%**	**4%**

NO (Not Occurring)

NE (Not Estimated)

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] The low and high estimates for total emissions were calculated separately through simulations and, hence, the low and high emission estimates for the sub-source categories do not sum to total emissions.

[c] Geothermal emissions added for reporting purposes, but an uncertainty analysis was not performed for CO_2 emissions from geothermal production.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

In order to ensure the quality of the CO_2 emission estimates from fossil fuel combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology used for estimating CO_2 emissions from fossil fuel combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated to determine whether any corrective actions were needed. Minor corrective actions were taken.

The UNFCCC reporting guidelines require countries to complete a "top-down" reference approach for estimating CO_2 emissions from fossil fuel combustion in addition to their “bottom-up” sectoral methodology. The reference approach (detailed in Annex 4) uses alternative methodologies and different data sources than those contained in this section of the report. The reference approach estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The reference approach assumes that once carbon-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the carbon in them is oxidized and released into the atmosphere. In the reference approach, accounting for actual consumption of fuels at the sectoral or sub-national level is not required. One difference between the two approaches is that emissions from carbon that was not stored during non-energy use of fuels are subtracted from the sectoral approach and reported separately (see Section 3.2). These emissions, however, are not subtracted in the reference approach. As a result, the reference approach emission estimates are comparable to those of the sectoral approach, with the exception that the Non-Energy Use (NEU) source category emissions are included in the reference approach (see Annex 4 for more details).

Recalculations Discussion

Several updates to activity data and emission factors lead to recalculations of previous year results. The major updates are as follows:

- EIA (2022a) updated energy consumption statistics across the time series relative to the previous Inventory. EIA revised sector allocations of propane for 2019 for petroleum consumption and the heat content of petroleum consumption, which impacted LPG by sector in 2019. Approximate heat rates for electricity and the heat content of electricity were revised for petroleum, total fossil fuels, and noncombustible renewable energy, which impacted electric power energy consumption by sector. Additionally, EIA has updated its data reported for biofuels including updating the methodology used for calculating consumption of Other Renewable Diesel.
- EPA also revised industrial HGL C contents to only include industrial propane consumption (excluding residential and commercial propane consumption) in the updated weighted factor calculation to align with EIA's revised heat contents and HGL fuel type categorization (EIA 2022a; ICF 2020). A discussion of the methodology used to develop the C content coefficients is presented in Annex 2.2. This resulted in an average annual increase of 0.2 percent in the weighted industrial HGL C contents.

All of the revisions discussed above resulted in the following impacts on emissions over time for petroleum:

- Petroleum emissions decreased by an average annual amount of 0.2 MMT CO_2 Eq. (less than 0.05 percent of petroleum emissions) from 1990 to 1999, which is mainly due to decreased emissions in the industrial sector as a result of the update in the weighted industrial HGL C contents.
- Similarly, petroleum emissions decreased by an average annual amount of 0.3 MMT CO_2 Eq. (less than 0.05 percent) from 2000 to 2007.
- Petroleum emissions decreased again by an average of annual amount of 1.8 MMT CO_2 Eq. at the end of the time-series from 2008 to 2019. In 2019, petroleum emissions by the residential sector increased by 4.4 MMT CO_2 Eq. relative to the previous Inventory. Petroleum emissions by the industrial and transportation sector decreased by 4.7 and 7.7 MMT CO_2 Eq respectively. This change in 2019 is due to EIA's revised sector allocations for propane and updates to biofuels data accounting.
- Across the time series, petroleum emissions from the transportation sector decreased by an average annual amount of 0.8 MMT CO_2 Eq. This decrease is due to updates to biofuels data by EIA.

Overall, these changes resulted in an average annual decrease of 0.7 MMT CO_2 Eq. (less than 0.05 percent) in CO_2 emissions from fossil fuel combustion for the period 1990 through 2019, relative to the previous Inventory. However, there were bigger absolute changes across the time series as discussed above.

Planned Improvements

To reduce uncertainty of CO_2 from fossil fuel combustion estimates for U.S. Territories, further expert elicitation may be conducted to better quantify the total uncertainty associated with emissions from U.S. Territories. Additionally, although not technically a fossil fuel, since geothermal energy-related CO_2 emissions are included for reporting purposes, further expert elicitation may be conducted to better quantify the total uncertainty associated with CO_2 emissions from geothermal energy use.

The availability of facility-level combustion emissions through EPA's GHGRP will continue to be examined to help better characterize the industrial sector's energy consumption in the United States and further classify total industrial sector fossil fuel combustion emissions by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC methodologies, though for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under the GHGRP may also include industrial process emissions.[47] In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from fossil fuel combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory.

Additional analyses will be conducted to align reported facility-level fuel types and IPCC fuel types per the national energy statistics. For example, additional work will look at CO_2 emissions from biomass to ensure they are separated in the facility-level reported data and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will continue to be relied upon.[48]

An ongoing planned improvement is to develop improved estimates of domestic waterborne fuel consumption. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. It may be possible to more accurately estimate domestic fuel use and emissions by using detailed data on marine ship activity. The feasibility of using domestic marine activity data to improve the estimates will continue to be investigated.

EPA is also evaluating the methods used to adjust for conversion of fuels and exports of CO_2. EPA is exploring the approach used to account for CO_2 transport, injection, and geologic storage, as part of this there may be changes made to accounting for CO_2 exports.

Finally, another ongoing planned improvement is to evaluate data availability to update the carbon and heat content of more fuel types accounted for in this Inventory. This update will impact consumption and emissions across all sectors and will improve consistency with EIA data as carbon and heat contents of fuels will be accounted for as annually variable and therefore improve accuracy across the time series. Some of the fuels considered in this effort include petroleum coke, residual fuel, and woody biomass.

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[47] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

[48] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

CH_4 and N_2O from Stationary Combustion

Methodology and Time-Series Consistency

Methane and N_2O emissions from stationary combustion were estimated by multiplying fossil fuel and wood consumption data by emission factors (by sector and fuel type for industrial, residential, commercial, and U.S. Territories; and by fuel and technology type for the electric power sector). The electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The activity data and emission factors used are described in the following subsections.

More detailed information on the methodology for calculating emissions from stationary combustion, including emission factors and activity data, is provided in Annex 3.1.

Industrial, Residential, Commercial, and U.S. Territories

National coal, natural gas, fuel oil, and wood consumption data were grouped by sector: industrial, commercial, residential, and U.S. Territories. For the CH_4 and N_2O emission estimates, consumption data for each fuel were obtained from EIA's *Monthly Energy Review* (EIA 2022a). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were provided separately by EIA's International Energy Statistics (EIA 2022b).[49] Fuel consumption for the industrial sector was adjusted to subtract out mobile source construction and agricultural use, which is reported under mobile sources. Construction and agricultural mobile source fuel use was obtained from EPA (2021) and FHWA (1996 through 2021). Estimates for wood biomass consumption for fuel combustion do not include municipal solid waste, tires, etc., that are reported as biomass by EIA. Non-CO_2 emissions from combustion of the biogenic portion of municipal solid waste and tires is included under waste incineration (Section 3.2). Estimates for natural gas combustion do not include biogas, and therefore non-CO_2 emissions from biogas are not included (see the Planned Improvements section, below). Tier 1 default emission factors for the industrial, commercial, and residential end-use sectors were provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). U.S. Territories' emission factors were estimated using the U.S. emission factors for the primary sector in which each fuel was combusted.

Electric Power Sector

The electric power sector uses a Tier 2 emission estimation methodology as fuel consumption for the electric power sector by control-technology type was based on EPA's Acid Rain Program Dataset (EPA 2022). Total fuel consumption in the electric power sector from EIA (2022a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2022) data. The combustion technology and fuel use data by facility obtained from EPA (2022) were only available from 1996 to 2020, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2022) to the total EIA (2022a) consumption for each year from 1990 to 1995.

Emissions were estimated by multiplying fossil fuel and wood consumption by technology-, fuel-, and country-specific Tier 2 emission factors. The Tier 2 emission factors used are based in part on emission factors published by

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[49] U.S. Territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, CH_4 and N_2O emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

EPA, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for coal wall-fired boilers, residual fuel oil, diesel oil and wood boilers, natural gas-fired turbines, and combined cycle natural gas units.[50] Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020 as discussed below. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from biomass use in Territories, but those emissions are assumed to be insignificant.

Uncertainty

Methane emission estimates from stationary sources exhibit high uncertainty, primarily due to difficulties in calculating emissions from wood combustion (i.e., fireplaces and wood stoves). The estimates of CH_4 and N_2O emissions presented are based on broad indicators of emissions (i.e., fuel use multiplied by an aggregate emission factor for different sectors), rather than specific emission processes (i.e., by combustion technology and type of emission control).

An uncertainty analysis was performed by primary fuel type for each end-use sector, using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, with @RISK software.

The uncertainty estimation model for this source category was developed by integrating the CH_4 and N_2O stationary source inventory estimation models with the model for CO_2 from fossil fuel combustion to realistically characterize the interaction (or endogenous correlation) between the variables of these three models. About 55 input variables were simulated for the uncertainty analysis of this source category (about 20 from the CO_2 emissions from fossil fuel combustion inventory estimation model and about 35 from the stationary source inventory models).

In developing the uncertainty estimation model, uniform distribution was assumed for all activity-related input variables and N_2O emission factors, based on the SAIC/EIA (2001) report.[51] For these variables, the uncertainty ranges were assigned to the input variables based on the data reported in SAIC/EIA (2001).[52] However, the CH_4 emission factors differ from those used by EIA. These factors and uncertainty ranges are based on IPCC default uncertainty estimates (IPCC 2006).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-18. Stationary combustion CH_4 emissions in 2020 (including biomass) were estimated to be between 5.3 and 17.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 34 percent below to 125 percent above the 2020 emission estimate of 7.9 MMT CO_2 Eq.[53] Stationary combustion N_2O emissions in 2020 (including biomass) were estimated to be between 17.6 and 35.0 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 24 percent below to 51 percent above the 2020 emission estimate of 23.2 MMT CO_2 Eq.

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[50] Several of the U.S. Tier 2 emission factors were used in IPCC (2006) as Tier 1 emission factors. See Table A-69 in Annex 3.1 for emission factors by technology type and fuel type for the electric power sector.

[51] SAIC/EIA (2001) characterizes the underlying probability density function for the input variables as a combination of uniform and normal distributions (the former distribution to represent the bias component and the latter to represent the random component). However, for purposes of the current uncertainty analysis, it was determined that uniform distribution was more appropriate to characterize the probability density function underlying each of these variables.

[52] In the SAIC/EIA (2001) report, the quantitative uncertainty estimates were developed for each of the three major fossil fuels used within each end-use sector; the variations within the sub-fuel types within each end-use sector were not modeled. However, for purposes of assigning uncertainty estimates to the sub-fuel type categories within each end-use sector in the current uncertainty analysis, SAIC/EIA (2001)-reported uncertainty estimates were extrapolated.

[53] The low emission estimates reported in this section have been rounded down to the nearest integer values and the high emission estimates have been rounded up to the nearest integer values.

Table 3-18: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Energy-Related Stationary Combustion, Including Biomass (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Stationary Combustion	CH_4	7.9	5.3	17.8	-34%	+125%
Stationary Combustion	N_2O	23.2	17.6	35.0	-24%	+51%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The uncertainties associated with the emission estimates of CH_4 and N_2O are greater than those associated with estimates of CO_2 from fossil fuel combustion, which mainly rely on the carbon content of the fuel combusted. Uncertainties in both CH_4 and N_2O estimates are due to the fact that emissions are estimated based on emission factors representing only a limited subset of combustion conditions. For the indirect greenhouse gases, uncertainties are partly due to assumptions concerning combustion technology types, age of equipment, emission factors used, and activity data projections.

QA/QC and Verification

In order to ensure the quality of the non-CO_2 emission estimates from stationary combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CH_4, N_2O, and the greenhouse gas precursors from stationary combustion in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated.

Recalculations Discussion

Methane and N_2O emissions from stationary sources (excluding CO_2) across the entire time series were revised due to revised data from EIA (2022a) relative to the previous Inventory. EIA (2022a) revised approximate heat rates for electricity and the heat content of electricity for petroleum and noncombustible renewable energy, which impacted electric power energy consumption by sector.

EIA also revised sector allocations for propane for 2019, which impacted LPG by sector. The historical data changes resulted in an average annual increase of 0.01 MMT CO_2 Eq. (0.1 percent) in CH_4 emissions, and an average annual change of less than 0.05 MMT CO_2 Eq. (less than 0.05 percent) in N_2O emissions for the 1990 through 2019 period.

Planned Improvements

Several items are being evaluated to improve the CH_4 and N_2O emission estimates from stationary combustion and to reduce uncertainty for U.S. Territories. Efforts will be taken to work with EIA and other agencies to improve the quality of the U.S. Territories data. Because these data are not broken out by stationary and mobile uses, further research will be aimed at trying to allocate consumption appropriately. In addition, the uncertainty of biomass emissions will be further investigated because it was expected that the exclusion of biomass from the estimates would reduce the uncertainty; and in actuality the exclusion of biomass increases the uncertainty. These improvements are not all-inclusive but are part of an ongoing analysis and efforts to continually improve these stationary combustion estimates from U.S. Territories.

Other forms of biomass-based gas consumption include biogas. EPA will examine EIA and GHGRP data on biogas collected and burned for energy use and determine if CH_4 and N_2O emissions from biogas can be included in future Inventories. EIA (2022a) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas.

CH_4 and N_2O from Mobile Combustion

Methodology and Time-Series Consistency

Estimates of CH_4 and N_2O emissions from mobile combustion were calculated by multiplying emission factors by measures of activity for each fuel and vehicle type (e.g., light-duty gasoline trucks). Activity data included vehicle miles traveled (VMT) for on-road vehicles and fuel consumption for non-road mobile sources. The activity data and emission factors used in the calculations are described in the subsections that follow. A complete discussion of the methodology used to estimate CH_4 and N_2O emissions from mobile combustion and the emission factors used in the calculations is provided in Annex 3.2.

On-Road Vehicles

Estimates of CH_4 and N_2O emissions from gasoline and diesel on-road vehicles are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle type, fuel type, model year, and emission control technology. Emission estimates for alternative fuel vehicles (AFVs) are based on VMT and emission factors (in grams of CH_4 and N_2O per mile) by vehicle and fuel type.[54]

CH_4 and N_2O emissions factors by vehicle type and emission tier for newer (starting with model year 2004) on-road gasoline vehicles were calculated by Browning (2019) from annual vehicle certification data compiled by EPA. CH_4 and N_2O emissions factors for older (model year 2003 and earlier) on-road gasoline vehicles were developed by ICF (2004). These earlier emission factors were derived from EPA, California Air Resources Board (CARB) and Environment and Climate Change Canada (ECCC) laboratory test results of different vehicle and control technology types. The EPA, CARB and ECCC tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments, since vehicles emit varying amounts of greenhouse gases depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was then analyzed to determine quantities of gases present. The emissions characteristics of driving segment 2 tests were used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were then recombined to approximate average driving characteristics, based upon the ratio of start to running emissions for each vehicle class from MOBILE6.2, an EPA emission factor model that predicts gram per mile emissions of CO_2, CO, HC, NO_x, and PM from vehicles under various conditions.[55]

Diesel on-road vehicle emission factors were developed by ICF (2006a). CH_4 and N_2O emissions factors for newer (starting at model year 2007) on-road diesel vehicles (those using engine aftertreatment systems) were calculated from annual vehicle certification data compiled by EPA.

CH_4 and N_2O emission factors for AFVs were developed based on the 2021 Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (ANL 2021). For light-duty trucks, EPA used a curve fit of 1999 through 2011 travel fractions for LDT1 and LDT2 (MOVES Source Type 31 for LDT1 and MOVES Source Type 32 for LDT2). For medium-duty vehicles, EPA used emission factors for light heavy-duty vocational trucks. For

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[54] Alternative fuel and advanced technology vehicles are those that can operate using a motor fuel other than gasoline or diesel. This includes electric or other bi-fuel or dual-fuel vehicles that may be partially powered by gasoline or diesel.

[55] Additional information regarding the MOBILE model can be found online at https://www.epa.gov/moves/description-and-history-mobile-highway-vehicle-emission-factor-model.

heavy-duty vehicles, EPA used emission factors for long-haul combination trucks. For buses, EPA used emission factors for transit buses. These values represent vehicle operations only (tank-to-wheels); upstream well-to-tank emissions are calculated elsewhere in the Inventory. Biodiesel CH_4 emission factors were corrected from GREET values to be the same as CH_4 emission factors for diesel vehicles. GREET overestimated biodiesel CH_4 emission factors based upon an incorrect CH_4-to-THC ratio for diesel vehicles with aftertreatment technology.

Annual VMT data for 1990 through 2020 were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System database as reported in Highway Statistics (FHWA 1996 through 2021).[56] VMT estimates were then allocated from FHWA's vehicle categories to fuel-specific vehicle categories using the calculated shares of vehicle fuel use for each vehicle category by fuel type reported in DOE (1993 through 2021) and information on total motor vehicle fuel consumption by fuel type from FHWA (1996 through 2021). VMT for AFVs were estimated based on Browning (2017 and 2018a). The age distributions of the U.S. vehicle fleet were obtained from EPA (2004, 2021b), and the average annual age-specific vehicle mileage accumulation of U.S. vehicles were obtained from EPA (2021b).

Control technology and standards data for on-road vehicles were obtained from EPA's Office of Transportation and Air Quality (EPA 2021c, 2021d, and 1998) and Browning (2005). These technologies and standards are defined in Annex 3.2, and were compiled from EPA (1994a, 1994b, 1998, 1999a) and IPCC (2006) sources.

Non-Road Mobile Sources

The non-road mobile category for CH_4 and N_2O includes ships and boats, aircraft, locomotives, and off-road sources (e.g., construction or agricultural equipment). For non-road sources, fuel-based emission factors are applied to data on fuel consumption, following the IPCC Tier 1 approach, for locomotives, aircraft, ships and boats. The Tier 2 approach would require separate fuel-based emissions factors by technology for which data are not available. For some of the non-road categories, 2-stroke and 4-stroke technologies are broken out and have separate emission factors; those cases could be considered a Tier 2 approach.

To estimate CH_4 and N_2O emissions from non-road mobile sources, fuel consumption data were employed as a measure of activity, and multiplied by fuel-specific emission factors (in grams of N_2O and CH_4 per kilogram of fuel consumed).[57] Activity data were obtained from AAR (2008 through 2021), APTA (2007 through 2021), RailInc (2014 through 2021), APTA (2006), BEA (1991 through 2015), Benson (2002 through 2004), DLA Energy (2021), DOC (1991 through 2020), DOE (1993 through 2021), DOT (1991 through 2021), EIA (2002, 2007, 2022), EIA (2021f), EIA (1991 through 2020), EPA (2021b), Esser (2003 through 2004), FAA (2022), FHWA (1996 through 2021),[58] Gaffney

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[56] The source of VMT data is FHWA Highway Statistics Table VM-1. In 2011, FHWA changed its methods for estimating data in the VM-1 table. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 1990 through 2010 Inventory and apply to the 2007 through 2020 time period. This resulted in large changes in VMT by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in the current Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[57] The consumption of international bunker fuels is not included in these activity data, but emissions related to the consumption of international bunker fuels are estimated separately under the International Bunker Fuels source category.

[58] This Inventory uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES model gasoline volumes to estimate non-road mobile source CH_4 and N_20 emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both non-road trucks and equipment. For construction and commercial/industrial category gasoline estimates, the 2014 and older MF-24 volumes represented non-road trucks only; therefore, the MOVES gasoline volumes for construction and commercial/industrial categories are added to the respective categories in the Inventory. Beginning in 2015, this addition is no longer necessary since the FHWA updated its methods for estimating on-road and non-road gasoline consumption. Among the method updates, FHWA now incorporates MOVES equipment gasoline volumes in the construction and commercial/industrial categories.

(2007), and Whorton (2006 through 2014). Emission factors for non-road modes were taken from IPCC (2006) and Browning (2020a and 2018b).

Uncertainty

A quantitative uncertainty analysis was conducted for the mobile source sector using the IPCC-recommended Approach 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique, using @RISK software. The uncertainty analysis was performed on 2020 estimates of CH_4 and N_2O emissions, incorporating probability distribution functions associated with the major input variables. For the purposes of this analysis, the uncertainty was modeled for the following four major sets of input variables: (1) VMT data, by on-road vehicle and fuel type, (2) emission factor data, by on-road vehicle, fuel, and control technology type, (3) fuel consumption, data, by non-road vehicle and equipment type, and (4) emission factor data, by non-road vehicle and equipment type.

Uncertainty analyses were not conducted for NO_x, CO, or NMVOC emissions. Emission factors for these gases have been extensively researched because emissions of these gases from motor vehicles are regulated in the United States, and the uncertainty in these emission estimates is believed to be relatively low. For more information, see Section 3.9 – Uncertainty Analysis of Emission Estimates. However, a much higher level of uncertainty is associated with CH_4 and N_2O emission factors due to limited emission test data, and because, unlike CO_2 emissions, the emission pathways of CH_4 and N_2O are highly complex.

Based on the uncertainty analysis, mobile combustion CH_4 emissions from all mobile sources in 2020 were estimated to be between 2.0 and 2.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 24 percent above the corresponding 2020 emission estimate of 2.2 MMT CO_2 Eq. Mobile combustion N_2O emissions from mobile sources in 2020 were estimated to be between 16.0 and 20.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 8 percent below to 19 percent above the corresponding 2020 emission estimate of 17.4 MMT CO_2 Eq.

Table 3-19: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Mobile Sources (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(Percent)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mobile Sources	CH_4	2.2	2.0	2.7	-8%	+24%
Mobile Sources	N_2O	17.4	16.0	20.7	-8%	+19%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

This uncertainty analysis is a continuation of a multi-year process for developing quantitative uncertainty estimates for this source category using the IPCC Approach 2 uncertainty estimation methodology. As a result, as new information becomes available, uncertainty characterization of input variables may be improved and revised. For additional information regarding uncertainty in emission estimates for CH_4 and N_2O please refer to the Uncertainty Annex. As discussed in Annex 5, data are unavailable to include estimates of CH_4 and N_2O emissions from any liquid fuel used in pipeline transport or some biomass used in transportation sources, but those emissions are assumed to be insignificant.

QA/QC and Verification

In order to ensure the quality of the emission estimates from mobile combustion, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The specific plan used for mobile combustion was updated prior to collection and analysis of this current year of data. The Tier 2 procedures focused on the emission factor and activity data sources, as well as the methodology used for estimating emissions. These procedures included a qualitative assessment of the emission estimates to determine whether they appear consistent with the most recent activity data and emission factors available. A comparison of historical emissions between the current Inventory and the previous Inventory was also conducted to ensure that the changes in estimates were consistent with the changes in activity data and emission factors.

Recalculations Discussion

Updates were made to CH_4 and N_2O emission factors for newer non-road gasoline and diesel vehicles. Previously, these emission factors were calculated using the updated 2006 IPCC Tier 3 guidance and the Nonroad component EPA's MOVES2014b model. Updated factors are calculated using the Nonroad component of MOVES3 model. CH_4 emission factors were calculated directly from MOVES3. N_2O emission factors were calculated using MOVES-Nonroad activity and emission factors in g/kWh by fuel type from the European Environment Agency. Updated emission factors were developed using EPA engine certification data for non-road small and large spark-ignition (SI) gasoline engines and compression-ignition diesel engines (model year 2011 and newer), as well as non-road motorcycles (model year 2006 and newer), SI marine engines (model year 2011 and newer), and diesel marine engines (model year 2000 and newer). Further refinements were made to the calculation of CH_4 and N_2O emission factors for non-road equipment. In previous Inventories, average emission factors by non-road equipment type and fuel type were applied to average engine power values. In the refined method, emission factors developed from certification data were binned by engine power, and emissions were calculated for each horsepower bin, non-road equipment type, and fuel type combination. These were then combined to determine emission factors for a given non-road equipment and fuel type.

The collective result of these changes was a net increase in CH_4 emissions and a decrease in N_2O emissions from mobile combustion relative to the previous Inventory. Methane emissions increased by 11.9 percent and N_2O emissions decreased by 1.3 percent. Furthermore, the adoption of the MOVES3 model for this update does not impact estimates of CO_2 emissions from transportation and non-transportation mobile sources.

Previously, heavy-duty diesel buses were grouped with heavy-duty diesel trucks under the heavy-duty diesel vehicle category. The updated approach calculates emissions from heavy-duty buses as a separate category. New emission factors specific to buses have been developed from EPA certification data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020 with one recent notable exception. An update by FHWA to the method for estimating on-road VMT created an inconsistency in on-road CH_4 and N_2O for the time periods 1990 to 2006 and 2007 to 2020. Details on the emission trends and methodological inconsistencies through time are described in the Methodology section above.

Planned Improvements

While the data used for this report represent the most accurate information available, several areas for improvement have been identified.

- Update emission factors for ships and non-recreational boats using residual fuel and distillate fuel, emission factors for locomotives using ultra low sulfur diesel, and emission factors for aircraft using jet fuel. The Inventory currently uses IPCC default values for these emission factors.
- Continue to explore potential improvements to estimates of domestic waterborne fuel consumption for future Inventories. The Inventory estimates for residual and distillate fuel used by ships and boats is based in part on data on bunker fuel use from the U.S. Department of Commerce. Domestic fuel consumption is estimated by subtracting fuel sold for international use from the total sold in the United States. Since 2015, all ships travelling within 200 nautical miles of the U.S. coastlines must use distillate fuels thereby overestimating the residual fuel used by U.S. vessels and underestimating distillate fuel use in these ships.

3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels (CRF Source Category 1A)

In addition to being combusted for energy, fossil fuels are also consumed for non-energy uses (NEU) in the United States. The fuels used for these purposes are diverse, including natural gas, hydrocarbon gas liquids (HGL),[59] asphalt (a viscous liquid mixture of heavy crude oil distillates), petroleum coke (manufactured from heavy oil), and coal (metallurgical) coke (manufactured from coking coal). The non-energy applications of these fuels are equally diverse, including feedstocks for the manufacture of plastics, rubber, synthetic fibers and other materials; reducing agents for the production of various metals and inorganic products; and products such as lubricants, waxes, and asphalt (IPCC 2006). Emissions from non-energy use of lubricants, paraffin waxes, bitumen / asphalt, and solvents are reported in the Energy sector, as opposed to the Industrial Processes and Product Use (IPPU) sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology (see Box 3-5). In addition, estimates of non-energy use emissions included here do not include emissions already reflected in the IPPU sector, e.g., fuels used as reducing agents. To avoid double counting, the "raw" non-energy fuel consumption data reported by EIA are reduced to account for these emissions already included under IPPU.

Carbon dioxide emissions arise from non-energy uses via several pathways. Emissions may occur during the manufacture of a product, as is the case in producing plastics or rubber from fuel-derived feedstocks. Additionally, emissions may occur during the product's lifetime, such as during solvent use. Overall, throughout the time series and across all uses, about 62 percent of the total C consumed for non-energy purposes was stored in products (e.g., plastics), and not released to the atmosphere; the remaining 38 percent was emitted.

There are several areas in which non-energy uses of fossil fuels are closely related to other parts of this Inventory. For example, some of the non-energy use products release CO_2 at the end of their commercial life when they are combusted after disposal; these emissions are reported separately within the Energy chapter in the Incineration of Waste source category. There are also net exports of petrochemical intermediate products that are not completely accounted for in the EIA data, and the Inventory calculations adjust for the effect of net exports on the mass of C in non-energy applications.

As shown in Table 3-20, fossil fuel emissions in 2020 from the non-energy uses of fossil fuels were 121.0 MMT CO_2 Eq., which constituted approximately 2.6 percent of overall fossil fuel emissions. In 2020, the consumption of fuels for non-energy uses (after the adjustments described above) was 5,570.6 TBtu (see Table 3-21). A portion of the C in the 5,570.6 TBtu of fuels was stored (229.6 MMT CO_2 Eq.), while the remaining portion was emitted (121.0 MMT CO_2 Eq.). Non-energy use emissions decreased by 4.6 percent from 2019 to 2020, mainly due to a decrease in industrial fuel use (specifically in the coking coal industry) potentially caused by the COVID-19 pandemic. See Annex 2.3 for more details.

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[59] HGL (formerly referred to as liquefied petroleum gas, or LPG) are hydrocarbons that occur as gases at atmospheric pressure and as liquids under higher pressures. HGLs include paraffins, such as ethane, propane, butanes, isobutane, and natural gasoline (formerly referred to as pentanes plus), and HGLs include olefins, such as ethylene, propylene, butylene and isobutylene. Adjustments were made in the 1990 to 2019 Inventory report to HGL activity data, carbon content coefficients, and heat contents HGL.

Table 3-20: CO_2 Emissions from Non-Energy Use Fossil Fuel Consumption (MMT CO_2 Eq. and Percent)

Year	1990	2005	2016	2017	2018	2019	2020
Potential Emissions	305.6	366.8	317.7	332.0	352.2	355.5	350.5
C Stored	193.4	237.9	218.2	219.4	223.4	228.8	229.6
Emissions as a % of Potential	37%	35%	31%	34%	37%	36%	35%
C Emitted	**112.2**	**128.9**	**99.5**	**112.6**	**128.9**	**126.8**	**121.0**

Note: NEU emissions presented in this table differ from the NEU emissions presented in CRF table 1.A(a)s4 as the CRF NEU emissions do not include NEU of lubricants and other petroleum in U.S. Territories. NEU emissions from U.S. Territories are reported under U.S. Territories in the CRF table 1.A(a)s4.

Methodology and Time-Series Consistency

The first step in estimating C stored in products was to determine the aggregate quantity of fossil fuels consumed for non-energy uses. The C content of these feedstock fuels is equivalent to potential emissions, or the product of consumption and the fuel-specific C content values. Both the non-energy fuel consumption and C content data were supplied by the EIA (2021b) (see Annex 2.1). Consumption values for industrial coking coal, petroleum coke, other oils, and natural gas in Table 3-21 and Table 3-22 have been adjusted to subtract non-energy uses that are included in the source categories of the Industrial Processes and Product Use chapter.[60] Consumption of natural gas, HGL, naphthas, other oils, and special naphtha were adjusted to subtract out net exports of these products that are not reflected in the raw data from EIA. Consumption values were also adjusted to subtract net exports of HGL components (e.g., propylene, ethane).

For the remaining non-energy uses, the quantity of C stored was estimated by multiplying the potential emissions by a storage factor.

- For several fuel types—petrochemical feedstocks (including natural gas for non-fertilizer uses, HGL, naphthas, other oils, still gas, special naphtha, and industrial other coal), asphalt and road oil, lubricants, and waxes—U.S. data on C stocks and flows were used to develop C storage factors, calculated as the ratio of (a) the C stored by the fuel's non-energy products to (b) the total C content of the fuel consumed. A lifecycle approach was used in the development of these factors in order to account for losses in the production process and during use. Because losses associated with municipal solid waste management are handled separately in the Energy sector under the Incineration of Waste source category, the storage factors do not account for losses at the disposal end of the life cycle.
- For industrial coking coal and distillate fuel oil, storage factors were taken from Marland and Rotty (1984).
- For the remaining fuel types (petroleum coke, miscellaneous products and other petroleum), IPCC (2006) does not provide guidance on storage factors, and assumptions were made based on the potential fate of C in the respective non-energy use products. Carbon dioxide emissions from carbide production are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke.

Table 3-21: Adjusted Consumption of Fossil Fuels for Non-Energy Uses (TBtu)

Year	1990	2005	2016	2017	2018	2019	2020
Industry	**4,317.5**	**5,115.0**	**4,833.0**	**5,089.5**	**5,447.7**	**5,484.1**	**5,447.7**
Industrial Coking Coal	NO	80.4	89.6	113.0	124.8	113.4	78.8

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[60] These source categories include Iron and Steel Production, Lead Production, Zinc Production, Ammonia Manufacture, Carbon Black Manufacture (included in Petrochemical Production), Titanium Dioxide Production, Ferroalloy Production, Silicon Carbide Production, and Aluminum Production.

Industrial Other Coal	7.6	11.0	9.5	9.5	9.5	9.5	9.5
Natural Gas to Chemical Plants	282.4	260.9	496.4	588.0	676.4	667.6	663.0
Asphalt & Road Oil	1,170.2	1,323.2	853.4	849.2	792.8	843.9	832.3
HGL[a]	1,217.7	1,609.9	2,127.9	2,193.3	2,506.5	2,550.3	2,656.5
Lubricants	186.3	160.2	135.1	124.9	122.0	118.3	107.4
Natural Gasoline[b]	117.5	95.4	53.1	81.7	105.3	155.0	163.6
Naphtha (<401 °F)	327.0	679.5	398.2	413.0	421.2	369.5	329.3
Other Oil (>401 °F)	663.6	499.5	204.6	242.9	219.1	212.1	195.5
Still Gas	36.7	67.7	166.1	163.8	166.9	158.7	145.4
Petroleum Coke	29.1	106.2	NO	NO	NO	NO	NO
Special Naphtha	101.1	60.9	89.0	95.3	87.0	89.5	80.7
Distillate Fuel Oil	7.0	16.0	5.8	5.8	5.8	5.8	5.8
Waxes	33.3	31.4	12.8	10.2	12.4	10.4	9.2
Miscellaneous Products	137.8	112.8	191.3	198.8	198.0	180.2	170.7
Transportation	**176.0**	**151.3**	**154.4**	**142.0**	**137.0**	**131.3**	**119.3**
Lubricants	176.0	151.3	154.4	142.0	137.0	131.3	119.3
U.S. Territories	**50.8**	**114.9**	**10.5**	**3.5**	**3.6**	**3.6**	**3.6**
Lubricants	0.7	4.6	1.0	1.0	1.0	1.0	1.0
Other Petroleum (Misc. Prod.)	50.1	110.3	9.5	2.4	2.5	2.6	2.6
Total	**4,544.4**	**5,381.2**	**4,997.9**	**5,234.9**	**5,588.3**	**5,619.1**	**5,570.6**

NO (Not Occurring)

[a] Excludes natural gasoline.

[b] Formerly referred to as "Pentanes Plus." This source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.

Table 3-22: 2020 Adjusted Non-Energy Use Fossil Fuel Consumption, Storage, and Emissions

Sector/Fuel Type	Adjusted Non-Energy Use[a] (TBtu)	Carbon Content Coefficient (MMT C/QBtu)	Potential Carbon (MMT C)	Storage Factor	Carbon Stored (MMT C)	Carbon Emissions (MMT C)	Carbon Emissions (MMT CO_2 Eq.)
Industry	**5,447.7**	**NA**	**93.1**	**NA**	**62.4**	**30.7**	**112.7**
Industrial Coking Coal	78.8	25.60	2.0	0.10	0.2	1.8	6.7
Industrial Other Coal	9.5	26.13	0.2	0.63	0.2	0.1	0.3
Natural Gas to Chemical Plants	663.0	14.47	9.6	0.63	6.0	3.6	13.1
Asphalt & Road Oil	832.3	20.55	17.1	1.00	17.0	0.1	0.3
HGL[b]	2,656.5	16.77	44.5	0.63	27.9	16.7	61.1
Lubricants	107.4	20.20	2.2	0.09	0.2	2.0	7.2
Natural Gasoline[c]	163.6	18.24	3.0	0.63	1.9	1.1	4.1
Naphtha (<401° F)	329.3	18.55	6.1	0.63	3.8	2.3	8.4
Other Oil (>401° F)	195.5	20.17	3.9	0.63	2.5	1.5	5.4
Still Gas	145.4	17.51	2.5	0.63	1.6	1.0	3.5
Petroleum Coke	NO	27.85	NO	0.30	NO	NO	NO
Special Naphtha	80.7	19.74	1.6	0.63	1.0	0.6	2.2
Distillate Fuel Oil	5.8	20.22	0.1	0.50	0.1	0.1	0.2
Waxes	9.2	19.80	0.2	0.58	0.1	0.1	0.3
Miscellaneous Products	170.7	NO	NO	NO	NO	NO	NO
Transportation	**119.3**	**NA**	**2.4**	**NA**	**0.2**	**2.2**	**8.0**
Lubricants	119.3	20.20	2.4	0.09	0.2	2.2	8.0

U.S. Territories	**3.6**	**NA**	**0.1**	**NA**	**0.0**	**0.1**	**0.2**
Lubricants	1.0	20.20	+	0.09	+	+	0.1
Other Petroleum (Misc. Prod.)	2.6	20.00	+	0.10	+	+	0.2
Total	**5,570.6**		**95.6**		**62.6**	**33.0**	**121.0**

+ Does not exceed 0.05 TBtu, MMT C, or MMT CO_2 Eq.
NA (Not Applicable)
NO (Not Occurring)
[a] To avoid double counting, net exports have been deducted.
[b] Excludes natural gasoline.
[c] Formerly referred to as "Pentanes Plus." This source has been adjusted and is reported separately from HGL to align with historic data and revised EIA terminology.
Note: Totals may not sum due to independent rounding.

Lastly, emissions were estimated by subtracting the C stored from the potential emissions (see Table 3-20). More detail on the methodology for calculating storage and emissions from each of these sources is provided in Annex 2.3.

Where storage factors were calculated specifically for the United States, data were obtained on (1) products such as asphalt, plastics, synthetic rubber, synthetic fibers, cleansers (soaps and detergents), pesticides, food additives, antifreeze and deicers (glycols), and silicones; and (2) industrial releases including energy recovery (waste gas from chemicals), Toxics Release Inventory (TRI) releases, hazardous waste incineration, and volatile organic compound, solvent, and non-combustion CO emissions. Data were taken from a variety of industry sources, government reports, and expert communications. Sources include EPA reports and databases such as compilations of air emission factors (EPA 2001), *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data* (EPA 2021b), *Toxics Release Inventory, 1998* (EPA 2000b), *Biennial Reporting System* (EPA 2000a, 2009), *Resource Conservation and Recovery Act Information System* (EPA 2013b, 2015, 2016b, 2018b, 2021a), pesticide sales and use estimates (EPA 1998, 1999, 2002, 2004, 2011, 2017), and the Chemical Data Access Tool (EPA 2014b); the EIA Manufacturer's Energy Consumption Survey (MECS) (EIA 1994, 1997, 2001, 2005, 2010, 2013, 2017, 2021a); the National Petrochemical & Refiners Association (NPRA 2002); the U.S. Census Bureau (1999, 2004, 2009, 2014, 2021); Bank of Canada (2012, 2013, 2014, 2016, 2017, 2018, 2019, 2020, 2021); Financial Planning Association (2006); INEGI (2006); the United States International Trade Commission (2021); Gosselin, Smith, and Hodge (1984); EPA's *Municipal Solid Waste (MSW) Facts and Figures* (EPA 2013, 2014a, 2016a, 2018a, 2019); the Rubber Manufacturers' Association (RMA 2009, 2011, 2014, 2016, 2018); the International Institute of Synthetic Rubber Products (IISRP 2000, 2003); the Fiber Economics Bureau (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012, 2013); the Independent Chemical Information Service (ICIS 2008, 2016); the EPA Chemical Data Access Tool (CDAT) (EPA 2014b); the American Chemistry Council (ACC 2003 through 2011, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021a); and the *Guide to the Business of Chemistry* (ACC 2021b). Specific data sources are listed in full detail in Annex 2.3.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020 as discussed below.

Box 3-5: Reporting of Lubricants, Waxes, and Asphalt and Road Oil Product Use in Energy Sector

IPCC (2006) provides methodological guidance to estimate emissions from the first use of fossil fuels as a product for primary purposes other than combustion for energy purposes (including lubricants, paraffin waxes, bitumen / asphalt, and solvents) under the IPPU sector.[61] In this Inventory, C storage and C emissions from

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[61] See for example Volume 3: Industrial Processes and Product Use, and Chapter 5: Non-Energy Products from Fuels and Solvent Use of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

product use of lubricants, waxes, and asphalt and road oil are reported under the Energy sector in the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category (CRF Source Category 1A5).[62]

The emissions are reported in the Energy sector, as opposed to the IPPU sector, to reflect national circumstances in its choice of methodology and to increase transparency of this source category's unique country-specific data sources and methodology. Although emissions from these non-energy uses are reported in the Energy chapter the methodologies used to determine emissions are compatible with the 2006 IPCC Guidelines. The country-specific methodology used for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category is based on a carbon balance (i.e., C inputs-outputs) calculation of the aggregate amount of fossil fuels used for non-energy uses, including inputs of lubricants, waxes, asphalt and road oil (see Table 3-22).

For those inputs, U.S. country-specific data on C stocks and flows are used to develop carbon storage factors, which are calculated as the ratio of the C stored by the fossil fuel non-energy products to the total C content of the fuel consumed, taking into account losses in the production process and during product use.[63] The country-specific methodology to reflect national circumstances starts with the aggregate amount of fossil fuels used for non-energy uses and applies a C balance calculation, breaking out the C emissions from non-energy use of lubricants, waxes, and asphalt and road oil. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance and to avoid double counting. Due to U.S. national circumstances, reporting these C emissions separately under IPPU would involve making artificial adjustments to allocate both the C inputs and C outputs of the non-energy use C balance. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting these non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use C carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. To avoid presenting an incomplete C balance and a less transparent approach for the Carbon Emitted from Non-Energy Uses of Fossil Fuels source category calculation, the entire calculation of C storage and C emissions is therefore conducted in the Non-Energy Uses of Fossil Fuels category calculation methodology, and both the C storage and C emissions for lubricants, waxes, and asphalt and road oil are reported under the Energy sector.

However, emissions from non-energy uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, Aluminum Production, Titanium Dioxide and zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances.

Uncertainty

An uncertainty analysis was conducted to quantify the uncertainty surrounding the estimates of emissions and storage factors from non-energy uses. This analysis, performed using @RISK software and the IPCC-recommended Approach 2 methodology (Monte Carlo Stochastic Simulation technique), provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the inventory estimate. The results presented below provide the 95 percent confidence interval, the range of values within which emissions are likely to fall, for this source category.

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[62] Non-methane volatile organic compound (NMVOC) emissions from solvent use are reported separately in the IPPU sector, following Chapter 5 of the *2006 IPCC Guidelines*.

[63] Data and calculations for lubricants and waxes and asphalt and road oil are in Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

As noted above, the non-energy use analysis is based on U.S.-specific storage factors for (1) feedstock materials (natural gas, HGL, natural gasoline, naphthas, other oils, still gas, special naphthas, and other industrial coal), (2) asphalt, (3) lubricants, and (4) waxes. For the remaining fuel types (the "other" category in Table 3-21 and Table 3-22) the storage factors were taken directly from IPCC (2006), where available, and otherwise assumptions were made based on the potential fate of carbon in the respective NEU products. To characterize uncertainty, five separate analyses were conducted, corresponding to each of the five categories. In all cases, statistical analyses or expert judgments of uncertainty were not available directly from the information sources for all the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-23 (emissions) and Table 3-24 (storage factors). Carbon emitted from non-energy uses of fossil fuels in 2020 was estimated to be between 76.3 and 180.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 37 percent below to 49 percent above the 2020 emission estimate of 121.0 MMT CO_2 Eq. The uncertainty in the emission estimates is a function of uncertainty in both the quantity of fuel used for non-energy purposes and the storage factor.

Table 3-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Non-Energy Uses of Fossil Fuels (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	98.1	56.0	159.4	-43%	+62%
Asphalt	CO_2	0.3	0.1	0.6	-59%	+121%
Lubricants	CO_2	15.3	12.7	17.8	-17%	+16%
Waxes	CO_2	0.3	0.2	0.6	-26%	+100%
Other	CO_2	7.0	1.4	8.1	-80%	+15%
Total	**CO_2**	**121.0**	**76.3**	**180.2**	**-37%**	**+49%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding.

Table 3-24: Approach 2 Quantitative Uncertainty Estimates for Storage Factors of Non-Energy Uses of Fossil Fuels (Percent)

Source	Gas	2020 Storage Factor (%)	Uncertainty Range Relative to Emission Estimate[a] (%)		(%, Relative)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Feedstocks	CO_2	62.6%	50.0%	73.1%	-20%	+17%
Asphalt	CO_2	99.6%	99.1%	99.8%	-0.5%	+0.3%
Lubricants	CO_2	9.2%	3.8%	17.6%	-58%	+92%
Waxes	CO_2	57.8%	47.4%	67.6%	-18%	+17%
Other	CO_2	11.5%	7.1%	83.3%	-38%	+622%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval, as a percentage of the inventory value (also expressed in percent terms).

As shown in Table 3-24, feedstocks and asphalt contribute least to overall storage factor uncertainty on a percentage basis. Although the feedstocks category—the largest use category in terms of total carbon flows—appears to have tight confidence limits, this is to some extent an artifact of the way the uncertainty analysis was structured. As discussed in Annex 2.3, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage values are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As is the case with the other uncertainty analyses discussed throughout this document, the uncertainty results above address only those factors that can be readily quantified. More details on the uncertainty analysis are provided in Annex 2.3.

QA/QC and Verification

In order to ensure the quality of the emission estimates from non-energy uses of fossil fuels, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. This effort included a general analysis, as well as portions of a category specific analysis for non-energy uses involving petrochemical feedstocks and for imports and exports. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and methodology for estimating the fate of C (in terms of storage and emissions) across the various end-uses of fossil C. Emission and storage totals for the different subcategories were compared, and trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors and to improve the transparency of the calculations, facilitating future QA/QC.

For petrochemical import and export data, special attention was paid to NAICS numbers and titles to verify that none had changed or been removed. Import and export totals were compared with 2019 totals as well as their trends across the time series.

It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels and industrial process emissions. For petrochemical feedstock production, our review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the Industrial Processes and Product Use (IPPU) emissions category for petrochemicals. Further data integration is not available at his time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers are unable to be used due to the data failing GHGRP CBI aggregation criteria.

Recalculations Discussion

Several updates to activity data factors lead to recalculations of previous year results. The major updates are as follows:

- EIA (2021b) updated energy consumption statistics across the time series relative to the previous Inventory, which resulted in a slight decrease in emissions from 1990 to 2019.
- ACC (2021b) updated polyester fiber and acetic acid production in 2019, which resulted in a slight decrease in emissions relative to the previous Inventory.
- U.S. International Trade Commission (2021) updated 2018 and 2019 import and export data, resulting in fewer net exports relative to the previous Inventory.
- U.S. Census Bureau (2021) released new shipment data, which increased historical cleanser shipment estimates from 2013 to 2019. Cleanser shipment data from 2013 to 2016 were updated to be linearly interpolated between the 2012 and 2017 Economic Census values, and data from 2018 to 2019 were proxied to the 2017 value.

Overall, these changes resulted in an average annual decrease of 0.6 MMT CO_2 Eq. (0.5 percent) in carbon emissions from non-energy uses of fossil fuels for the period 1990 through 2019, relative to the previous Inventory.

Planned Improvements

There are several future improvements planned:

- More accurate accounting of C in petrochemical feedstocks. EPA has worked with EIA to determine the cause of input/output discrepancies in the C mass balance contained within the NEU model. In the future, two strategies to reduce or eliminate this discrepancy will continue to be pursued as part of quality control procedures. First, accounting of C in imports and exports will be improved. The import/export adjustment methodology will be examined to ensure that net exports of intermediaries such as ethylene and propylene are fully accounted for. Second, the use of top-down C input calculation in estimating emissions will be reconsidered. Alternative approaches that rely more substantially on the bottom-up C output calculation will be considered instead.
- Improving the uncertainty analysis. Most of the input parameter distributions are based on professional judgment rather than rigorous statistical characterizations of uncertainty.
- Better characterizing flows of fossil C. Additional fates may be researched, including the fossil C load in organic chemical wastewaters, plasticizers, adhesives, films, paints, and coatings. There is also a need to further clarify the treatment of fuel additives and backflows (especially methyl tert-butyl ether, MTBE).
- Reviewing the trends in fossil fuel consumption for non-energy uses. Annual consumption for several fuel types is highly variable across the time series, including industrial coking coal and other petroleum. A better understanding of these trends will be pursued to identify any mischaracterized or misreported fuel consumption for non-energy uses.
- Updating the average C content of solvents was researched, since the entire time series depends on one year's worth of solvent composition data. The data on C emissions from solvents that were readily available do not provide composition data for all categories of solvent emissions and also have conflicting definitions for volatile organic compounds, the source of emissive C in solvents. Additional sources of solvents data will be investigated in order to update the C content assumptions.
- Updating the average C content of cleansers (soaps and detergents) was researched; although production and consumption data for cleansers are published every 5 years by the Census Bureau, the composition (C content) of cleansers has not been recently updated. Recently available composition data sources may facilitate updating the average C content for this category.
- Revising the methodology for consumption, production, and C content of plastics was researched; because of recent changes to the type of data publicly available for plastics, the NEU model for plastics applies data obtained from personal communications. Potential revisions to the plastics methodology to account for the recent changes in published data will be investigated.
- Although U.S.-specific storage factors have been developed for feedstocks, asphalt, lubricants, and waxes, default values from IPCC are still used for two of the non-energy fuel types (industrial coking coal, distillate oil), and broad assumptions are being used for miscellaneous products and other petroleum. Over the long term, there are plans to improve these storage factors by analyzing C fate similar to those described in Annex 2.3 or deferring to more updated default storage factors from IPCC where available.
- Reviewing the storage of carbon black across various sectors in the Inventory; in particular, the carbon black abraded and stored in tires.
- Assess the current method and/or identify new data sources (e.g., EIA) for estimating emissions from ammonia/fertilizer use of natural gas.
- Investigate EIA NEU and MECS data to update, as needed, adjustments made for ammonia production and "natural gas to chemical plants, other uses" and "natural gas to other" non-energy uses, including iron and steel production, in energy uses and IPPU.

3.3 Incineration of Waste (CRF Source Category 1A5)

Incineration is used to manage about 7 to 19 percent of the solid wastes generated in the United States, depending on the source of the estimate and the scope of materials included in the definition of solid waste (EPA 2000; EPA 2020; Goldstein and Madtes 2001; Kaufman et al. 2004; Simmons et al. 2006; van Haaren et al. 2010). In the context of this section, waste includes all municipal solid waste (MSW) as well as scrap tires. In the United States, incineration of MSW tends to occur at waste-to-energy facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Energy chapter. Similarly, scrap tires are combusted for energy recovery in industrial and utility boilers, pulp and paper mills, and cement kilns. Incineration of waste results in conversion of the organic inputs to CO_2. According to the *2006 IPCC Guidelines*, when the CO_2 emitted is of fossil origin, it is counted as a net anthropogenic emission of CO_2 to the atmosphere. Thus, the emissions from waste incineration are calculated by estimating the quantity of waste combusted and the fraction of the waste that is C derived from fossil sources.

Most of the organic materials in MSW are of biogenic origin (e.g., paper, yard trimmings), and have their net C flows accounted for under the Land Use, Land-Use Change, and Forestry chapter. However, some components of MSW and scrap tires—plastics, synthetic rubber, synthetic fibers, and carbon black—are of fossil origin. Plastics in the U.S. waste stream are primarily in the form of containers, packaging, and durable goods. Rubber is found in durable goods, such as carpets, and in non-durable goods, such as clothing and footwear. Fibers in MSW are predominantly from clothing and home furnishings. As noted above, scrap tires (which contain synthetic rubber and carbon black) are also considered a “non-hazardous” waste and are included in the waste incineration estimate, though waste disposal practices for tires differ from MSW. Estimates on emissions from hazardous waste incineration can be found in Annex 2.3 and are accounted for as part of the C mass balance for non-energy uses of fossil fuels.

Approximately 27.6 million metric tons of MSW were incinerated in 2020 (EPA 2020b). Carbon dioxide emissions from incineration of waste increased 1.5 percent since 1990, to an estimated 13.1 MMT CO_2 (13,133 kt) in 2020. Emissions across the time series are shown in Table 3-25 and Table 3-26.

Waste incineration is also a source of CH_4 and N_2O emissions (De Soete 1993; IPCC 2006). Methane emissions from the incineration of waste were estimated to be less than 0.05 MMT CO_2 Eq. (less than 0.05 kt CH_4) in 2020 and have remained steady since 1990. Nitrous oxide emissions from the incineration of waste were estimated to be 0.4 MMT CO_2 Eq. (1.4 kt N_2O) in 2020 and have decreased by 13 percent since 1990. This decrease is driven by the decrease in total MSW incinerated.

Table 3-25: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	12.9	13.3	14.4	13.2	13.3	12.9	13.1
CH_4	+	+	+	+	+	+	+
N_2O	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Total	**13.4**	**13.7**	**14.8**	**13.6**	**13.8**	**13.4**	**13.5**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 3-26: CO_2, CH_4, and N_2O Emissions from the Incineration of Waste (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	12,937	13,283	14,356	13,161	13,339	12,948	13,133
CH_4	+	+	+	+	+	+	+
N_2O	2	1	1	1	1	1	1

+ Does not exceed 0.05 kt.

Methodology and Time-Series Consistency

Municipal Solid Waste Incineration

To determine both CO_2 and non-CO_2 emissions from the incineration of waste, the tonnage of waste incinerated and an estimated emissions factor are needed. Emission estimates from the incineration of tires are discussed separately. Data for total waste incinerated was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC), EPA's Greenhouse Gas Reporting Program (GHGRP), and the U.S. Energy Information Administration (EIA). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA determined the MSW incineration tonnages based on data availability and accuracy throughout the time series.

- 1990-2006: MSW incineration tonnages are from Biocycle incineration data. Tire incineration data from RMA are removed to arrive at MSW incinerated without tires
- 2006-2010: MSW incineration tonnages are an average of Biocycle (with RMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with RMA tire data tonnage removed).
- 2011-2020: MSW incineration tonnages are from EPA's GHGRP data.

Table 3-27 provides the estimated tons of MSW incinerated including and excluding tires.

Table 3-27: Municipal Solid Waste Incinerated (Metric Tons)

Year	Waste Incinerated *(excluding tires)*	Waste Incinerated *(including tires)*
1990	33,344,839	33,766,239
2005	26,486,414	28,631,054
2016	29,704,817	31,534,322
2017	28,574,258	30,310,598
2018	29,162,364	30,853,949
2019	28,174,311	29,821,141
2020	27,586,271	29,233,101

Sources: BioCycle, EPA Facts and Figures, ERC, GHGRP, EIA, RMA.

CO_2 Emissions from MSW Excluding Scrap Tires

Fossil CO_2 emission factors were calculated from EPA's GHGRP data for non-biogenic sources. Using GHGRP-reported emissions for CH_4 and N_2O and assumed emission factors, the tonnage of waste incinerated, excluding tires, was derived. Methane and N_2O emissions and assumed emission factors were used to estimate the amount of MSW combusted in terms of energy content. The energy content of MSW combusted was then converted into tonnage based on assumed MSW heating value. Two estimates were generated (one for CH_4 and one for N_2O) and the two were averaged together. Dividing fossil CO_2 emissions from GHGRP FLIGHT data for MSW combustors by this estimated tonnage yielded an annual CO_2 emission factor. As this data was only available following 2011, all years prior use an average of the emission factors from 2011 through 2020.

Finally, CO_2 emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil CO_2 emission factors are shown in Table 3-28**.**

Table 3-28: Calculated Fossil CO_2 Content per Ton Waste Incinerated (kg CO_2/Short Ton Incinerated)

	1990		2005		2016	2017	2018	2019	2020
CO_2 Emission Factors	367		367		381	360	361	363	377

CO_2 Emissions from Scrap Tires

Scrap tires contain several types of synthetic rubber, carbon black, and synthetic fibers. Each type of synthetic rubber has a discrete C content, and carbon black is 100 percent C. For synthetic rubber and carbon black in scrap tires, information was obtained biannually from U.S. Scrap Tire Management Summary for 2005 through 2019 data (RMA 2020). Information about scrap tire composition was taken from the Rubber Manufacturers' Association internet site (RMA 2012a). Emissions of CO_2 were calculated based on the amount of scrap tires used for fuel and the synthetic rubber and carbon black content of scrap tires. The mass of incinerated material is multiplied by its C content to calculate the total amount of carbon stored. 2020 values are proxied from 2019 data. More detail on the methodology for calculating emissions from each of these waste incineration sources is provided in Annex 3.7. Table 3-29 provides CO_2 emissions from combustion of waste tires.

Table 3-29: CO_2 Emissions from Combustion of Tires (MMT CO_2 Eq.)

	1990		2005		2016	2017	2018	2019	2020
Synthetic Rubber	0.3		1.6		1.4	1.3	1.3	1.2	1.2
C Black	0.4		2.0		1.7	1.6	1.5	1.5	1.5
Total	**0.7**		**13.7**		**3.0**	**2.9**	**2.8**	**2.7**	**2.7**

Non-CO_2 Emissions

Incineration of waste also results in emissions of CH_4 and N_2O. These emissions were calculated by multiplying the total estimated mass of waste incinerated, including tires, by the respective emission factors. The emission factors for CH_4 and N_2O emissions per quantity of MSW combusted are default emission factors for the default continuously-fed stoker unit MSW incineration technology type and were taken from IPCC (2006).

Uncertainty

An Approach 2 Monte Carlo analysis was performed to determine the level of uncertainty surrounding the estimates of CO_2 emissions and N_2O emissions from the incineration of waste (given the very low emissions for CH_4, no uncertainty estimate was derived). IPCC Approach 2 analysis allows the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for most variables; thus, uncertainty estimates for these variables were determined using assumptions based on source category knowledge and the known uncertainty estimates for the waste generation variables.

The uncertainties in the waste incineration emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include reported CO_2 emissions; N_2O and CH_4 emissions factors, and tire synthetic rubber and black carbon contents. The highest levels of uncertainty surround the reported emissions from GHGRP; the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, C content of C black).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-30. Waste incineration CO_2 emissions in 2020 were estimated to be between 10.8 and 15.3 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 17 percent below to 17 percent above the 2020 emission estimate of 13.1 MMT CO_2 Eq. Also at a 95 percent confidence level, waste incineration N_2O emissions in 2020 were estimated to be between 0.2

and 1.0 MMT CO_2 Eq. This indicates a range of 53 percent below to 162 percent above the 2020 emission estimate of 0.4 MMT CO_2 Eq.

Table 3-30: Approach 2 Quantitative Uncertainty Estimates for CO_2 and N_2O from the Incineration of Waste (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Incineration of Waste	CO_2	13.1	10.8	15.3	-17%	17%
Incineration of Waste	N_2O	0.4	0.2	1.0	-53%	162%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates from waste incineration, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and specifically focused on the emission factor and activity data sources and methodology used for estimating emissions from incineration of waste. Trends across the time series were analyzed to determine whether any corrective actions were needed. Corrective actions were taken to rectify minor errors in the use of activity data.

Recalculations Discussion

Waste incineration estimates in the current Inventory were derived following a new methodology relying on different data sources than previously used. Specifically:

- Waste tonnage estimates for 2006 through 2019 relied on several new data sources. Prior years relied on proxied data from 2011 from Shin (2014).
- For 1990 through 2020, CO_2 emissions were calculated with a new methodology using a carbon emission factor calculated from EPA's GHGRP data. An emission factor for years prior to 2011 was estimated using the average of 2011 through 2020 emission factors. The previous methodology relied on generation, disposal, and incineration rates of synthetic fibers, plastics, and synthetic rubber and the accompanying carbon contents to calculate CO_2 emissions for incineration of these materials. The methodology for estimating tire CO_2 emissions did not change.
- Non-CO_2 emissions were calculated using the same IPCC (2006) default factor as previous years. However, MSW incineration activity data changed based on the revisions to the methodology.

As a result of the changes in data and methodology, CO_2 emissions in 2019 increased 13 percent relative to the previous Inventory and there was an average annual increase of 20 percent over the time series. Non-CO_2 emissions for both CH_4 and N_2O increased by 30 percent relative to the prior Inventory. The observed change in emissions is primarily due to the difference in MSW tonnages starting in 2010 and the revision of the CO_2 emission factor across the time series.

Planned Improvements

Currently, emission estimates for the biomass and biomass-based fuels source category included in this Inventory are limited to woody biomass, ethanol, and biodiesel. EPA will incorporate emissions from biogenic components of MSW to biomass and biomass-based fuels or waste incineration in future Inventory assessments.

3.4 Coal Mining (CRF Source Category 1B1a)

Three types of coal mining-related activities release CH_4 and CO_2 to the atmosphere: underground mining, surface mining, and post-mining (i.e., coal-handling) activities. While surface coal mines account for the majority of U.S. coal production, underground coal mines contribute the largest share of fugitive CH_4 emissions (see Table 3-32 and Table 3-33) due to the higher CH_4 content of coal in the deeper underground coal seams. In 2020, 196 underground coal mines and 350 surface mines were operating in the United States (EIA 2021). In recent years, the total number of active coal mines in the United States has declined. In 2020, the United States was the fifth largest coal producer in the world (485 MMT), after China (3,764 MMT), India (760 MMT), Indonesia (564 MMT), and Australia (493 MMT) (IEA 2021).

Table 3-31: Coal Production (kt)

Year	Underground		Surface		Total	
	Number of Mines	Production	Number of Mines	Production	Number of Mines	Production
1990	1,683	384,244	1,656	546,808	3,339	931,052
2005	586	334,399	789	691,447	1,398	1,025,846
2016	251	228,707	439	431,282	690	659,989
2017	237	247,778	434	454,301	671	702,080
2018	236	249,804	430	435,521	666	685,325
2019	226	242,557	432	397,750	658	640,307
2020	196	177,380	350	307,944	546	485,324

Fugitive CH_4 Emissions

Underground coal mines liberate CH_4 from ventilation systems and from degasification systems. Ventilation systems pump air through the mine workings to dilute noxious gases and ensure worker safety; these systems can exhaust significant amounts of CH_4 to the atmosphere in low concentrations. Degasification systems are wells drilled from the surface or boreholes drilled inside the mine that remove large, often highly concentrated volumes of CH_4 before, during, or after mining. Some mines recover and use CH_4 generated from ventilation and degasification systems, thereby reducing emissions to the atmosphere.

Surface coal mines liberate CH_4 as the overburden is removed and the coal is exposed to the atmosphere. Methane emissions are normally a function of coal rank (a classification related to the percentage of carbon in the coal) and depth. Surface coal mines typically produce lower-rank coals and remove less than 250 feet of overburden, so their level of emissions is much lower than from underground mines.

In addition, CH_4 is released during post-mining activities, as the coal is processed, transported, and stored for use.

Total CH_4 emissions in 2020 were estimated to be 1,648 kt (41.2 MMT CO_2 Eq.), a decline of approximately 57 percent since 1990 (see Table 3-32and Table 3-33). In 2020, underground mines accounted for approximately 76 percent of total emissions, surface mines accounted for 12 percent, and post-mining activities accounted for 12 percent. In 2020, total CH_4 emissions from coal mining decreased by approximately 13 percent relative to the previous year. This decrease was due to a decrease in annual coal production. The amount of CH_4 recovered and used in 2020 decreased by approximately 3 percent compared to 2019 levels.

Table 3-32: CH_4 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Underground (UG) Mining	**74.2**	**42.0**	**40.7**	**40.7**	**38.9**	**34.5**	**31.4**
Liberated	80.8	59.7	56.9	58.1	57.7	50.3	46.8
Recovered & Used	(6.6)	(17.7)	(16.2)	(17.4)	(18.8)	(15.8)	(15.4)
Surface Mining	**10.8**	**11.9**	**6.8**	**7.2**	**7.0**	**6.4**	**4.9**
Post-Mining (UG)	**9.2**	**7.6**	**4.8**	**5.3**	**5.3**	**5.2**	**3.9**
Post-Mining (Surface)	**2.3**	**2.6**	**1.5**	**1.6**	**1.5**	**1.4**	**1.1**
Total	**96.5**	**64.1**	**53.8**	**54.8**	**52.7**	**47.4**	**41.2**

Note: Parentheses indicate negative values.

Table 3-33: CH_4 Emissions from Coal Mining (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Underground (UG) Mining	**2,968**	**1,682**	**1,629**	**1,626**	**1,556**	**1,379**	**1,257**
Liberated	3,231	2,388	2,277	2,324	2,308	2,011	1,871
Recovered & Used	(263)	(706)	(648)	(698)	(752)	(633)	(614)
Surface Mining	**430**	**475**	**273**	**290**	**280**	**255**	**194**
Post-Mining (UG)	**368**	**306**	**193**	**213**	**212**	**206**	**155**
Post-Mining (Surface)	**93**	**103**	**59**	**63**	**61**	**55**	**42**
Total	**3,860**	**2,565**	**2,154**	**2,191**	**2,109**	**1,895**	**1,648**

Note: Parentheses indicate negative values.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 3 method for estimating CH_4 emissions from underground coal mining and an IPCC Tier 2 method for estimating CH_4 emissions from surface mining and post-mining activities (for coal production from both underground mines and surface mines). The methodology for estimating CH_4 emissions from coal mining consists of two steps:

- Estimate CH_4 emissions from underground mines. These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total CH_4 liberated. The CH_4 recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- Estimate CH_4 emissions from surface mines and post-mining activities. Unlike the methodology for underground mines, which uses mine-specific data, the methodology for estimating emissions from surface mines and post-mining activities consists of multiplying basin-specific coal production by basin-specific gas content and an emission factor.

Step 1: Estimate CH_4 Liberated and CH_4 Emitted from Underground Mines

Underground mines generate CH_4 from ventilation systems and degasification systems. Some mines recover and use the liberated CH_4, thereby reducing emissions to the atmosphere. Total CH_4 emitted from underground mines equals the CH_4 liberated from ventilation systems, plus the CH_4 liberated from degasification systems, minus the CH_4 recovered and used.

Step 1.1: Estimate CH_4 Liberated from Ventilation Systems

To estimate CH_4 liberated from ventilation systems, EPA uses data collected through its Greenhouse Gas Reporting Program (GHGRP)[64] (Subpart FF, "Underground Coal Mines"), data provided by the U.S. Mine Safety and Health Administration (MSHA) (MSHA 2021), and occasionally data collected from other sources on a site-specific level (e.g., state gas production databases). Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 17,525 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2021).[65] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems; they have the option of recording and reporting their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the United States with detectable CH_4 concentrations.[66]

Since 2013, ventilation CH_4 emission estimates have been calculated based on both quarterly GHGRP data submitted by underground mines and on quarterly measurement data obtained directly from MSHA. Because not all mines report under EPA's GHGRP, the emissions of the mines that do not report must be calculated using MSHA data. The MSHA data also serves as a quality assurance tool for validating GHGRP data. For GHGRP data, reported quarterly ventilation methane emissions (metric tons) are summed for each mine to develop mine-specific annual ventilation emissions. For MSHA data, the average daily CH_4 emission rate for each mine is determined using the CH_4 total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily CH_4 emission rate is then multiplied by 365 days to estimate annual ventilation CH_4 emissions for the MSHA dataset.

Step 1.2: Estimate CH_4 Liberated from Degasification Systems

Particularly gassy underground mines also use degasification systems (e.g., wells or boreholes) to remove CH_4 before, during, or after mining. This CH_4 can then be collected for use or vented to the atmosphere. Twenty mines used degasification systems in 2020 and 19 of these mines reported the CH_4 removed through these systems to EPA's GHGRP under Subpart FF (EPA 2021). Based on the weekly measurements reported to EPA's GHGRP, degasification data summaries for each mine are added to estimate the CH_4 liberated from degasification systems. Thirteen of the 20 mines with degasification systems had operational CH_4 recovery and use projects (see step 1.3 below).[67]

Degasification data reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of CH_4 liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate CH_4 liberated from degasification systems at 15 of the 20 mines that used degasification systems in 2020. Data from state gas well production databases were used exclusively for a single mine and state gas well production data were used to supplement GHGRP degasification data for the remaining four mines (DMME 2021; GSA 2021; WVGES 2021).

For pre-mining wells, cumulative degasification volumes that occur prior to the well being mined through are attributed to the mine in the inventory year in which the well is mined through.[68] EPA's GHGRP does not require

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[64] In implementing improvements and integrating data from EPA's GHGRP, EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

[65] Underground coal mines report to EPA under Subpart FF of the GHGRP (40 CFR Part 98). In 2020, 71 underground coal mines reported to the program.

[66] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[67] Several of the mines venting CH_4 from degasification systems use a small portion of the gas to fuel gob well blowers in remote locations where electricity is not available. However, this CH_4 use is not considered to be a formal recovery and use project.

[68] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF.[69] Most pre-mining wells drilled from the surface are considered coalbed methane wells prior to mine-through and associated CH_4 emissions are reported under another subpart of the GHGRP (Subpart W, "Petroleum and Natural Gas Systems"). As a result, GHGRP data must be supplemented to estimate cumulative degasification volumes that occurred prior to well mine-through. There were five mines with degasification systems that include pre-mining wells that were mined through in 2020. For four of these mines, GHGRP data were supplemented with historical data from state gas well production databases (DMME 2021; ERG 2021; GSA 2021; WVGES 2021), as well as with mine-specific information regarding the locations and dates on which the pre-mining wells were mined through (JWR 2010; El Paso 2009; ERG 2021). State gas well production data were exclusively used for a single mine (GSA 2021).

Step 1.3: Estimate CH_4 Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)

Thirteen mines had CH_4 recovery and use projects in place in 2020, including one mine that had two recovery and use projects. Thirteen of these projects involved degasification systems, in place at twelve mines, and one involved a ventilation air methane abatement project (VAM). Eleven of these mines sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. One mine used recovered CH_4 to heat mine ventilation air (data were unavailable for estimating CH_4 recovery at this mine). One mine destroyed the recovered CH_4 (VAM) using regenerative thermal oxidation (RTO) without energy recovery.

The CH_4 recovered and used (or destroyed) at the thirteen mines described above are estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the CH_4 recovered and used from seven of the 12 mines that deployed degasification systems in 2020. Based on weekly measurements, the GHGRP degasification destruction data summaries for each mine are added together to estimate the CH_4 recovered and used from degasification systems.
- State sales data were used to estimate CH_4 recovered and used from the remaining five mines that deployed degasification systems in 2020 (DMME 2021, ERG 2021, GSA 2021, and WVGES 2021). These five mines intersected pre-mining wells in 2020. Supplemental information is used for these mines because estimating CH_4 recovery and use from pre-mining wells requires additional data not reported under Subpart FF of EPA's GHGRP (see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The supplemental data is obtained from state gas production databases as well as mine-specific information on the timing of mined-through pre-mining wells.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2021).

Step 2: Estimate CH_4 Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* (EIA 2021) is multiplied by basin-specific CH_4 contents (EPA 1996, 2005) and a 150 percent emission factor (to account for CH_4 from over- and under-burden) to estimate CH_4 emissions (King 1994; Saghafi 2013). For post-mining activities, basin-specific coal production is multiplied by basin-specific CH_4 contents and a mid-range 32.5 percent emission factor for CH_4 desorption during coal transportation and storage (Creedy 1993). Basin-specific in situ gas content data were compiled from AAPG (1984) and USBM (1986).

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[69] This applies for pre-drainage in years prior to the well being mined through. Beginning with the year the well is mined through, the annual volume of CH_4 liberated from a pre-drainage well is reported under Subpart FF of EPA's GHGRP.

Fugitive CO_2 Emissions

Methane and CO_2 are naturally occurring in coal seams and are collectively referred to as coal seam gas. These gases remain trapped in the coal seam until coal is mined (i.e., coal seam is exposed and fractured during mining operations). Fugitive CO_2 emissions occur during underground coal mining, surface coal mining, and post-mining activities. Methods and data to estimate fugitive CO_2 emissions from underground and surface coal mining are presented in the sections below. Fugitive CO_2 emissions from post-mining activities were not estimated due to the lack of an IPCC method and unavailability of data.

Total fugitive CO_2 emissions in 2020 were estimated to be 2,169 kt (2.2 MMT CO_2 Eq.), a decline of approximately 53 percent since 1990. In 2020, underground mines accounted for approximately 89 percent of total fugitive CO_2 emissions. In 2020, total fugitive CO_2 emissions from coal mining decreased by approximately 27 percent relative to the previous year. This decrease was due to a decrease in annual coal production.

Table 3-34: CO_2 Emissions from Coal Mining (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Underground (UG) Mining	**4.2**	**3.6**	**2.5**	**2.7**	**2.7**	**2.6**	**1.9**
Liberated	4.2	3.6	2.5	2.7	2.7	2.6	1.9
Recovered & Used	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Flaring	NO	NO	+	+	+	+	+
Surface Mining	**0.4**	**0.6**	**0.3**	**0.4**	**0.4**	**0.3**	**0.2**
Total	**4.6**	**4.2**	**2.8**	**3.1**	**3.1**	**3.0**	**2.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NO (Not Occurring)

Note: Parentheses indicate negative values.

Table 3-35: CO_2 Emissions from Coal Mining (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Underground (UG) Mining	**4,164**	**3,610**	**2,499**	**2,699**	**2,714**	**2,629**	**1,919**
Liberated	4,171	3,630	2,483	2,690	2,712	2,633	1,926
Recovered & Used	(8)	(20)	(18)	(20)	(21)	(18)	(18)
Flaring	NO	NO	34	29	24	14	11
Surface Mining	**443**	**560**	**349**	**368**	**353**	**322**	**249**
Total	**4,606**	**4,170**	**2,848**	**3,067**	**3,067**	**2,951**	**2,169**

NO (Not Occurring)

Note: Parentheses indicate negative values.

Methodology and Time-Series Consistency

EPA uses an IPCC Tier 1 method for estimating fugitive CO_2 emissions from underground coal mining and surface mining (IPCC 2019). IPCC methods and data to estimate fugitive CO_2 emissions from post-mining activities (for both underground and surface coal mining) are currently not available.

Step 1: Underground Mining

EPA used the following overarching IPCC equation to estimate fugitive CO_2 emissions from underground coal mines (IPCC 2019):

Equation 3-1: Estimating Fugitive CO_2 Emissions From Underground Mines

$$\begin{aligned}&Total\ CO_2\ from\ Underground\ Mines\\ &\qquad = CO_2\ from\ underground\ mining\ - Amount\ of\ CO_2\ in\ gas\ recovered\\ &\qquad + CO_2\ from\ methane\ flaring\end{aligned}$$

Step 1.1: Estimate Fugitive CO_2 Emissions From Underground Mining

EPA estimated fugitive CO_2 emissions from underground mining using the IPCC Tier 1 emission factor (5.9 m^3/metric ton) and annual coal production from underground mines (EIA 2021). The underground mining default emission factor accounts for all the fugitive CO_2 likely to be emitted from underground coal mining. Therefore, the amount of CO_2 from coal seam gas recovered and utilized for energy is subtracted from underground mining estimates in Step 2, below. Under IPCC methods, the CO_2 emissions from gas recovered and utilized for energy use (e.g., injected into a natural gas pipeline) are reported under other sectors of the Inventory (e.g., stationary combustion of fossil fuel or oil and natural gas systems) and not under the coal mining sector.

Step 1.2: Estimate Amount of CO_2 In Coal Seam Gas Recovered for Energy Purposes

EPA estimated fugitive CO_2 emissions from coal seam gas recovered and utilized for energy purposes by using the IPCC Tier 1 default emission factor (19.57 metric tons CO_2/million cubic meters of coal bed methane (CBM) produced) and quantity of coal seam gas recovered and utilized. Data on annual quantity of coal seam gas recovered and utilized are available from GHGRP and state sales data (GHGRP 2021; DMME 2021; ERG 2021; GSA 2021; WVGES 2021). The quantity of coal seam gas recovered and destroyed without energy recovery (e.g., VAM projects) is deducted from the total coal seam gas recovered quantity.

Step 1.3: Estimate Fugitive CO_2 Emissions From Flaring

The IPCC method includes combustion CO_2 emissions from gas recovered for non-energy uses (i.e., flaring, or catalytic oxidation) under fugitive CO_2 emission estimates for underground coal mining. In effect, these emissions, though occurring through stationary combustion, are categorized as fugitive emissions in the Inventory. EPA estimated CO_2 emissions from methane flaring using the following equation:

Equation 3-2: Estimating CO_2 Emissions From Drained Methane Flared Or Catalytically Oxidized

$$\begin{aligned} CO_2\ from\ flaring \\ &= 0.98\ \times Volume\ of\ methane\ flared \times Conversion\ Factor \\ &\times Stoichiometric\ Mass\ Factor \end{aligned}$$

Currently there is only a single mine that reports catalytic oxidation of recovered methane through flaring without energy use. Annual data for 2020 were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2021).

Step 2: Surface Mining

EPA estimated fugitive CO_2 emissions from surface mining using the IPCC Tier 1 emission factor (0.44 m^3/metric ton) and annual coal production from surface mines (EIA 2021).

Uncertainty

A quantitative uncertainty analysis was conducted for the coal mining source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. Because emission estimates of CH_4 from underground ventilation systems were based on actual measurement data from EPA's GHGRP or from MSHA, uncertainty is relatively low. A degree of imprecision was introduced because the ventilation air measurements used were not continuous but rather quarterly instantaneous readings that were used to determine the average annual emission rates. Additionally, the measurement equipment used can be expected to have resulted in an average of 10 percent overestimation of annual CH_4 emissions (Mutmansky & Wang 2000). Equipment measurement uncertainty is applied to GHGRP data.

Estimates of CH_4 liberated and recovered by degasification systems are relatively certain for utilized CH_4 because of the availability of EPA's GHGRP data and state gas sales information. Many of the liberation and recovery estimates use data on wells within 100 feet of a mined area. However, uncertainty exists concerning the radius of influence of each well. The number of wells counted, and thus the liberated CH_4 and avoided emissions, may vary if the drainage area is found to be larger or smaller than estimated.

EPA's GHGRP requires weekly CH_4 monitoring of mines that report degasification systems, and continuous CH_4 monitoring is required for CH_4 utilized on- or off-site. Since 2012, GHGRP data have been used to estimate CH_4 emissions from vented degasification wells, reducing the uncertainty associated with prior MSHA estimates used for this sub-source. Beginning in 2013, GHGRP data were also used for determining CH_4 recovery and use at mines without publicly available gas usage or sales records, which has reduced the uncertainty from previous estimation methods that were based on information from coal industry contacts.

Surface mining and post-mining emissions are associated with considerably more uncertainty than underground mines, because of the difficulty in developing accurate emission factors from field measurements. However, since underground coal mining, as a general matter, results in significantly larger CH_4 emissions due to production of higher-rank coal and greater depth, and estimated emissions from underground mining constitute the majority of estimated total coal mining CH_4 emissions, the uncertainty associated with underground emissions is the primary factor that determines overall uncertainty.

The major sources of uncertainty for estimates of fugitive CO_2 emissions are the Tier 1 IPCC default emission factors used for underground mining (-50 percent to +100 percent) and surface mining (-67 percent to +200 percent) (IPCC 2019). Additional sources of uncertainty for fugitive CO_2 emission estimates include EIA's annual coal production data and data used for gas recovery projects, such as GHGRP data, state gas sales data, and VAM estimates for the single mine that operates an active VAM project. Uncertainty ranges for these additional data sources are already available, as these are the same data sources used for CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-36. Coal mining CH_4 emissions in 2020 were estimated to be between 37.4 and 48.2 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 9.2 percent below to 17.1 percent above the 2020 emission estimate of 41.2 MMT CO_2 Eq. Coal mining fugitive CO_2 emissions in 2020 were estimated to be between 0.7 and 3.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68.3 percent below to 76.3 percent above the 2020 emission estimate of 2.2 MMT CO_2 Eq.

Table 3-36: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Coal Mining (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Coal Mining	CH_4	41.2	37.4	48.2	-9.2%	+17.1%
Coal Mining	CO_2	2.2	0.7	3.8	-68.3%	+76.3%

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for coal mining, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating fugitive emissions from coal mining. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Emission estimates for coal mining rely in large part on data reported by coal mines to EPA's GHGRP. EPA verifies annual facility-level reports through a multi-step process to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. All reports submitted to EPA are evaluated by electronic validation and verification checks. If potential errors are identified, EPA will notify the reporter, who can resolve the issue either by providing an acceptable response describing why the flagged issue is not an error or by correcting the flagged issue and resubmitting their annual report. Additional QA/QC and verification procedures occur for each GHGRP subpart. In 2021, a single facility resubmitted its 2020 annual CH_4 emissions data (i.e., mine vent emissions) under subpart FF to correct data reporting issues in its initial submission.

Recalculations Discussion

State gas sales production values were updated for three mines as part of normal data updates conducted by states. Data were updated for 2012 to 2014 and 2016 for one mine, for 2018 and 2019 for the second mine, and for 2019 for the third mine. These changes resulted in slightly lower degasification CH_4 emissions and CH_4 emissions avoided from underground mining for 2012 (0.04 percent) and 2016 (0.9 percent); and slightly higher degasification and avoided emissions in the remaining years (0.02 to 1.0 percent) with the highest change in 2019 (1 percent). The change in both the degasification emissions and emissions avoided is less than 0.05 percent over the 2012 to 2019 time series, compared to the previous Inventory.

Planned Improvements

EPA is assessing planned improvements for future reports, but at this time has no specific planned improvements for estimating CH_4 and CO_2 emissions from underground and surface mining and CH_4 emissions from post-mining. Updates on planned improvements will be included in the next Inventory submission.

3.5 Abandoned Underground Coal Mines (CRF Source Category 1B1a)

Underground coal mines contribute the largest share of coal mine methane (CMM) emissions, with active underground mines the leading source of underground emissions. However, mines also continue to release CH_4 after closure. As mines mature and coal seams are mined through, mines are closed and abandoned. Many are sealed and some flood through intrusion of groundwater or surface water into the void. Shafts or portals are generally filled with gravel and capped with a concrete seal, while vent pipes and boreholes are plugged in a manner similar to oil and gas wells. Some abandoned mines are vented to the atmosphere to prevent the buildup of CH_4 that may find its way to surface structures through overburden fractures. As work stops within the mines, CH_4 liberation decreases but it does not stop completely. Following an initial decline, abandoned mines can liberate CH_4 at a near-steady rate over an extended period of time, or if flooded, produce gas for only a few years. The gas can migrate to the surface through the conduits described above, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when CH_4 migrates to the surface through cracks and fissures in the strata overlying the coal mine. The following factors influence abandoned mine emissions:

- Time since abandonment;
- Gas content and adsorption characteristics of coal;
- CH_4 flow capacity of the mine;
- Mine flooding;
- Presence of vent holes; and
- Mine seals.

Annual gross abandoned mine CH_4 emissions ranged from 7.2 to 10.8 MMT CO_2 Eq. from 1990 to 2020, varying, in general, by less than 1 percent to approximately 19 percent from year to year. Fluctuations were due mainly to the number of mines closed during a given year as well as the magnitude of the emissions from those mines when active. Gross abandoned mine emissions peaked in 1996 (10.8 MMT CO_2 Eq.) due to the large number of gassy mine[70] closures from 1994 to 1996 (72 gassy mines closed during the three-year period). In spite of this rapid rise, abandoned mine emissions have been generally on the decline since 1996. Since 2002, there have been fewer than twelve gassy mine closures each year. In 2020 there were three gassy mine closures. Gross abandoned mine emissions decreased slightly from 8.5 MMT CO_2 Eq. (341 kt CH_4) in 2019 to 8.4 (335 kt CH_4) MMT CO_2 Eq. in 2020 (see Table 3-37 and Table 3-38). Gross emissions are reduced by CH_4 recovered and used at 45 mines, resulting in net emissions in 2020 of 5.8 MMT CO_2 Eq (231 kt CH_4).

Table 3-37: CH_4 Emissions from Abandoned Coal Mines (MMT CO_2 Eq.)

Activity	1990		2005		2016	2017	2018	2019	2020
Abandoned Underground Mines	7.2		8.4		9.5	9.2	8.9	8.5	8.4
Recovered & Used	NO		(1.8)		(2.8)	(2.7)	(2.7)	(2.6)	(2.6)
Total	**7.2**		**6.6**		**6.7**	**6.4**	**6.2**	**5.9**	**5.8**

NO (Not Occurring)

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Table 3-38: CH_4 Emissions from Abandoned Coal Mines (kt)

Activity	1990		2005		2016	2017	2018	2019	2020
Abandoned Underground Mines	288		334		380	367	355	341	335
Recovered & Used	NO		(70)		(112)	(109)	(107)	(104)	(104)
Total	**288**		**264**		**268**	**257**	**247**	**237**	**231**

NO (Not Occurring)

Notes: Parentheses indicate negative values. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Estimating CH_4 emissions from an abandoned coal mine requires predicting the emissions of a mine from the time of abandonment through the inventory year of interest. The flow of CH_4 from the coal to the mine void is primarily dependent on the mine's emissions when active and the extent to which the mine is flooded or sealed. The CH_4 emission rate before abandonment reflects the gas content of the coal, the rate of coal mining, and the flow capacity of the mine in much the same way as the initial rate of a water-free conventional gas well reflects the gas content of the producing formation and the flow capacity of the well. A well or a mine that produces gas from a coal seam and the surrounding strata will produce less gas through time as the reservoir of gas is depleted. Depletion of a reservoir will follow a predictable pattern depending on the interplay of a variety of natural physical conditions imposed on the reservoir. The depletion of a reservoir is commonly modeled by mathematical equations and mapped as a type curve. Type curves, which are referred to as decline curves, have been developed for abandoned coal mines. Existing data on abandoned mine emissions through time, although sparse, appear to fit the hyperbolic type of decline curve used in forecasting production from natural gas wells.

To estimate CH_4 emissions over time for a given abandoned mine, it is necessary to apply a decline function, initiated upon abandonment, to that mine. In the analysis, mines were grouped by coal basin with the assumption that they will generally have the same initial pressures, permeability and isotherm. As CH_4 leaves the system, the reservoir pressure (Pr) declines as described by the isotherm's characteristics. The emission rate declines because the mine pressure (Pw) is essentially constant at atmospheric pressure for a vented mine, and the productivity index (PI), which is expressed as the flow rate per unit of pressure change, is essentially constant at the pressures of interest (atmospheric to 30 psia). The CH_4 flow rate is determined by the laws of gas flow through porous media, such as Darcy's Law. A rate-time equation can be generated that can be used to predict future emissions. This decline through time is hyperbolic in nature and can be empirically expressed as:

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[70] A mine is considered a "gassy" mine if it emits more than 100 thousand cubic feet of CH_4 per day (100 mcfd).

Equation 3-3: Decline Function to Estimate Venting Abandoned Mine Methane Emissions

$$q = q_i\,(1 + bD_i t)^{(-1/b)}$$

where,

q = Gas flow rate at time t in million cubic feet per day (mmcfd)
q_i = Initial gas flow rate at time zero (t_o), mmcfd
b = The hyperbolic exponent, dimensionless
D_i = Initial decline rate, 1/year
t = Elapsed time from t_o (years)

This equation is applied to mines of various initial emission rates that have similar initial pressures, permeability and adsorption isotherms (EPA 2004).

The decline curves created to model the gas emission rate of coal mines must account for factors that decrease the rate of emissions after mining activities cease, such as sealing and flooding. Based on field measurement data, it was assumed that most U.S. mines prone to flooding will become completely flooded within eight years and therefore will no longer have any measurable CH_4 emissions. Based on this assumption, an average decline rate for flooded mines was established by fitting a decline curve to emissions from field measurements. An exponential equation was developed from emissions data measured at eight abandoned mines known to be filling with water located in two of the five basins. Using a least squares, curve-fitting algorithm, emissions data were matched to the exponential equation shown below. For this analysis of flooded abandoned mines, there was not enough data to establish basin-specific equations, as was done with the vented, non-flooding mines (EPA 2004). This decline through time can be empirically expressed as:

Equation 3-4: Decline Function to Estimate Flooded Abandoned Mine Methane Emissions

$$q = q_i e^{(-Dt)}$$

where,

q = Gas flow rate at time t in mmcfd
q_i = Initial gas flow rate at time zero (t_o), mmcfd
D = Decline rate, 1/year
t = Elapsed time from t_o (years)

Seals have an inhibiting effect on the rate of flow of CH_4 into the atmosphere compared to the flow rate that would exist if the mine had an open vent. The total volume emitted will be the same, but emissions will occur over a longer period of time. The methodology, therefore, treats the emissions prediction from a sealed mine similarly to the emissions prediction from a vented mine, but uses a lower initial rate depending on the degree of sealing. A computational fluid dynamics simulator was used with the conceptual abandoned mine model to predict the decline curve for inhibited flow. The percent sealed is defined as 100 × (1 – [initial emissions from sealed mine / emission rate at abandonment prior to sealing]). Significant differences are seen between 50 percent, 80 percent and 95 percent closure. These decline curves were therefore used as the high, middle, and low values for emissions from sealed mines (EPA 2004).

For active coal mines, those mines producing over 100 thousand cubic feet per day (mcfd) of CH_4 account for about 98 percent of all CH_4 emissions. This same relationship is assumed for abandoned mines. It was determined that the 529 abandoned mines closed after 1972 produced CH_4 emissions greater than 100 mcfd when active. Further, the status of 302 of the 529 mines (or 57 percent) is known to be either: 1) vented to the atmosphere; 2) sealed to some degree (either earthen or concrete seals); or 3) flooded (enough to inhibit CH_4 flow to the atmosphere). The remaining 43 percent of the mines whose status is unknown were placed in one of these three categories by applying a probability distribution analysis based on the known status of other mines located in the same coal basin (EPA 2004). Table 3-39 presents the count of mines by post-abandonment state, based on EPA's probability distribution analysis.

Table 3-39: Number of Gassy Abandoned Mines Present in U.S. Basins in 2020, Grouped by Class According to Post-Abandonment State

Basin	Sealed	Vented	Flooded	Total Known	Unknown	Total Mines
Central Appl.	43	25	50	118	144	262
Illinois	34	3	14	51	31	82
Northern Appl.	48	23	15	86	38	124
Warrior Basin	0	0	16	16	0	16
Western Basins	28	4	2	34	10	44
Total	**153**	**55**	**97**	**305**	**223**	**528**

Inputs to the decline equation require the average CH_4 emission rate prior to abandonment and the date of abandonment. Generally, these data are available for mines abandoned after 1971; however, such data are largely unknown for mines closed before 1972. Information that is readily available, such as coal production by state and county, is helpful but does not provide enough data to directly employ the methodology used to calculate emissions from mines abandoned before 1972. It is assumed that pre-1972 mines are governed by the same physical, geologic, and hydrologic constraints that apply to post-1971 mines; thus, their emissions may be characterized by the same decline curves.

During the 1970s, 78 percent of CH_4 emissions from coal mining came from seventeen counties in seven states. Mine closure dates were obtained for two states, Colorado and Illinois, for the hundred-year period extending from 1900 through 1999. The data were used to establish a frequency of mine closure histogram (by decade) and applied to the other five states with gassy mine closures. As a result, basin-specific decline curve equations were applied to the 145 gassy coal mines estimated to have closed between 1920 and 1971 in the U.S., representing 78 percent of the emissions. State-specific, initial emission rates were used based on average coal mine CH_4 emission rates during the 1970s (EPA 2004).

Abandoned mine emission estimates are based on all closed mines known to have active mine CH_4 ventilation emission rates greater than 100 mcfd at the time of abandonment. For example, for 1990 the analysis included 145 mines closed before 1972 and 258 mines closed between 1972 and 1990. Initial emission rates based on MSHA reports, time of abandonment, and basin-specific decline curves influenced by a number of factors were used to calculate annual emissions for each mine in the database (MSHA 2021). Coal mine degasification data are not available for years prior to 1990, thus the initial emission rates used reflect only ventilation emissions for pre-1990 closures. Methane degasification amounts were added to the quantity of CH_4 vented to determine the total CH_4 liberation rate for all mines that closed between 1992 and 2020. Since the sample of gassy mines described above is assumed to account for 78 percent of the pre-1972 and 98 percent of the post-1971 abandoned mine emissions, the modeled results were multiplied by 1.22 and 1.02, respectively, to account for all U.S. abandoned mine emissions.

From 1993 through 2020, emission totals were downwardly adjusted to reflect CH_4 emissions avoided from those abandoned mines with CH_4 recovery and use or destruction systems. The Inventory totals were not adjusted for abandoned mine CH_4 emissions avoided from 1990 through 1992, because no data was reported for abandoned coal mine CH_4 recovery and use or destruction projects during that time.

Uncertainty

A quantitative uncertainty analysis was conducted for the abandoned coal mine source category using the IPCC-recommended Approach 2 uncertainty estimation methodology. The uncertainty analysis provides for the specification of probability density functions for key variables within a computational structure that mirrors the calculation of the Inventory estimate. The results provide the range within which, with 95 percent certainty, emissions from this source category are likely to fall.

As discussed above, the parameters for which values must be estimated for each mine to predict its decline curve are: 1) the coal's adsorption isotherm; 2) CH_4 flow capacity as expressed by permeability; and 3) pressure at abandonment. Because these parameters are not available for each mine, a methodological approach to estimating emissions was used that generates a probability distribution of potential outcomes based on the most likely value and the probable range of values for each parameter. The range of values is not meant to capture the extreme values, but rather values that represent the highest and lowest quartile of the cumulative probability density function of each parameter. Once the low, mid, and high values are selected, they are applied to a probability density function.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 3-40. Annual abandoned coal mine CH_4 emissions in 2020 were estimated to be between 4.5 and 6.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 22 percent below to 20 percent above the 2020 emission estimate of 5.8 MMT CO_2 Eq. One of the reasons for the relatively narrow range is that mine-specific data is available for use in the methodology for mines closed in 1972 and later years. Emissions from mines closed prior to 1972 have the largest degree of uncertainty because no mine-specific CH_4 liberation rates at the time of abandonment exist.

Table 3-40: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Abandoned Underground Coal Mines (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Underground Coal Mines	CH_4	5.8	4.5	6.9	-21.9%	+19.5%

[a] Range of emission estimates predicted by Monte Carlo Simulation for a 95 percent confidence interval.

QA/QC and Verification

In order to ensure the quality of the emission estimates for abandoned coal mines, general (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and reported emissions data used for estimating emissions from abandoned coal mines. Trends across the time series were analyzed to determine whether any corrective actions were needed.

Recalculations Discussion

No recalculations were performed for prior year estimates in the time series.

3.6 Petroleum Systems (CRF Source Category 1B2a)

This IPCC category (1B2a) is for fugitive emissions from petroleum systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Methane emissions from petroleum systems are primarily associated with onshore and offshore crude oil exploration, production, transportation, and refining operations. During these activities, CH_4 is released to the atmosphere as emissions from leaks, venting (including emissions from operational upsets), and flaring. Carbon dioxide emissions from petroleum systems are primarily associated with onshore and offshore crude oil production and refining operations. Note, CO_2 emissions in petroleum systems exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in the fossil fuel combustion chapter (see Section 3). Emissions of N_2O from petroleum systems are primarily associated with flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from petroleum systems in 2020 were 70.4 MMT CO_2 Eq., an increase of 23 percent from 1990, primarily due to increases in CO_2 emissions. Total emissions increased by 23 percent from 2010 levels, and have decreased by 19 percent since 2019. Total CO_2 emissions from petroleum systems in 2020 were 30.2 MMT CO_2 (30,156 kt CO_2), 3.1 times higher than in 1990. Total CO_2 emissions in 2020 were 2.0 times higher than in 2010 and 35 percent lower than in 2019. Total CH_4 emissions from petroleum systems in 2020 were 40.2 MMT CO_2 Eq. (1,609 kt CH_4), a decrease of 16 percent from 1990. Since 2010, total CH_4 emissions decreased by 4 percent; and since 2019, CH_4 emissions decreased by 0.3 percent. Total N_2O emissions from petroleum systems in 2020 were 0.04 MMT CO_2 Eq. (0.13 kt N_2O), 2.5 times higher than in 1990, 1.9 times higher than in 2010, and 18 percent lower than in 2019. Since 1990, U.S. oil production has increased by 54 percent. In 2020, production was 106 percent higher than in 2010 and 8 percent lower than in 2019.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the entire Inventory's time series (i.e., 1990 to 2020) to ensure that the trend is representative of changes in emissions levels. Recalculations in petroleum systems in this year's Inventory include:

- Updates to well counts, oil and gas production volumes, and produced water volumes using the most recent data from Enverus and the United States Energy Information Administration (EIA)
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions

The Recalculations Discussion section below provides more details on the updated methods.

Exploration. Exploration includes well drilling, testing, and completions. Exploration accounts for less than 1 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2020. The predominant sources of CH_4 emissions from exploration are hydraulically fractured oil well completions. Other sources include well testing, well drilling, and well completions without hydraulic fracturing. Since 1990, exploration CH_4 emissions have decreased 92 percent, and while the number of hydraulically fractured wells completed increased 64 percent, there were decreases in the fraction of such completions without reduced emissions completions (RECs) or flaring. Emissions of CH_4 from exploration were highest in 2012, over 30 times higher than in 2020; and lowest in 2020. Emissions of CH_4 from exploration decreased 27 percent from 2019 to 2020, due to a decrease in emissions from hydraulically fractured oil well completions without RECs or flaring. Exploration accounts for 3 percent of total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2020. Emissions of CO_2 from exploration in 2020 were 2.4 times higher than in 1990, and decreased by 64 percent from 2019, due to a large decrease in the number of hydraulically fractured oil well completions (by 50% from 2019). Emissions of CO_2 from exploration were highest in 2014, over 4 times higher than in 2020. Exploration accounts for 1 percent of total N_2O emissions from petroleum systems in 2020. Emissions of N_2O from exploration in 2020 are 2.3 times higher than in 1990, and 59 percent lower than in 2019, due to the abovementioned changes in hydraulically fractured oil well completions with flaring.

Production. Production accounts for 97 percent of total CH_4 emissions (including leaks, vents, and flaring) from petroleum systems in 2020. The predominant sources of emissions from production field operations are pneumatic controllers, offshore oil platforms, equipment leaks, gas engines, produced water, chemical injection pumps, and associated gas flaring. In 2020, these seven sources together accounted for 92 percent of the CH_4 emissions from production. Since 1990, CH_4 emissions from production have decreased by 10 percent due to decreases in emissions from offshore platforms and tanks. Overall, production segment CH_4 emissions increased by less than 0.5 percent from 2019 levels due primarily to increased pneumatic controller emissions. Production emissions account for 83 percent of the total CO_2 emissions (including leaks, vents, and flaring) from petroleum systems in 2020. The principal sources of CO_2 emissions are associated gas flaring, miscellaneous production flaring, and oil tanks with flares. In 2020, these three sources together accounted for 97 percent of the CO_2 emissions from production. In 2020, CO_2 emissions from production were 4.2 times higher than in 1990, due to increases in flaring emissions from associated gas flaring, miscellaneous production flaring, and tanks. Overall, in 2020, production segment CO_2 emissions decreased by 36 percent from 2019 levels primarily due to decreases in associated gas flaring and miscellaneous production flaring in the Permian and Williston Basins. Production emissions accounted for 65 percent of the total N_2O emissions from petroleum systems in 2020. The principal sources of N_2O emissions are associated gas flaring, oil tanks with flares, miscellaneous production flaring, and offshore flaring. In 2020, N_2O emissions from production were 4.4 times higher than in 1990 and were 18 percent lower than in 2019.

Crude Oil Transportation. Emissions from crude oil transportation account for a very small percentage of the total emissions (including leaks, vents, and flaring) from petroleum systems. Crude oil transportation activities account for less than 1 percent of total CH_4 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 74 percent of CH_4 emissions from crude oil transportation. Since 1990, CH_4 emissions from transportation have increased by 32 percent. In 2020, CH_4 emissions from transportation decreased by 4 percent from 2019 levels. Crude oil transportation activities account for less than 0.01 percent of total CO_2 emissions from petroleum systems. Emissions from tanks, marine loading, and truck loading operations account for 74 percent of CO_2 emissions from crude oil transportation.

Crude Oil Refining. Crude oil refining processes and systems account for 2 percent of total fugitive (including leaks, vents, and flaring) CH_4 emissions from petroleum systems. This low share is because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries. There is a negligible amount of CH_4 in all refined products. Within refineries, flaring accounts for 52 percent of the CH_4 emissions, while delayed cokers, uncontrolled blowdowns, and equipment leaks account for 14, 13 and 9 percent, respectively. Fugitive CH_4 emissions from refining of crude oil have increased by 15 percent since 1990, and decreased 13 percent from 2019; however, like the transportation subcategory, this increase has had little effect on the overall emissions of CH_4 from petroleum systems. Crude oil refining processes and systems account for 14 percent of total fugitive (including leaks, vents, and flaring) CO_2 emissions from petroleum systems. Of the total fugitive CO_2 emissions from refining, almost all (about 99 percent) of it comes from flaring.[71] Since 1990, refinery fugitive CO_2 emissions increased by 32 percent and have decreased by 15 percent from the 2019 levels, due to a decrease in flaring. Flaring occurring at crude oil refining processes and systems accounts for 34 percent of total fugitive N_2O emissions from petroleum systems. In 2020, refinery fugitive N_2O emissions increased by 39 percent since 1990, and decreased by 15 percent from 2019 levels.

Table 3-41: Total Greenhouse Gas Emissions (CO_2, CH_4, and N_2O) from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	4.2	5.7	1.9	2.3	3.7	2.8	1.2
Production	49.1	43.1	55.4	58.5	67.4	78.0	63.9
Transportation	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Crude Refining	4.0	4.5	4.8	4.6	4.6	6.0	5.1
Total	**57.4**	**53.4**	**62.3**	**65.6**	**75.9**	**87.1**	**70.4**

Note: Totals may not sum due to independent rounding.

Table 3-42: CH_4 Emissions from Petroleum Systems (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	**3.8**	**5.3**	**0.6**	**0.4**	**0.5**	**0.4**	**0.3**
Production	**43.1**	**35.2**	**38.8**	**39.0**	**37.1**	**38.8**	**38.9**
Pneumatic Controllers	18.4	17.7	20.6	20.9	18.2	18.3	21.3
Offshore Production	8.8	6.5	5.1	5.1	4.9	4.9	4.8
Equipment Leaks	2.0	2.2	2.5	2.5	2.5	2.5	2.4
Gas Engines	2.0	1.8	2.2	2.2	2.3	2.3	2.2
Produced Water	2.3	1.6	2.0	2.1	2.3	2.4	2.2
Chemical Injection Pumps	1.2	1.7	2.0	2.0	2.0	2.0	1.9

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[71] Petroleum Systems includes fugitive emissions (leaks, venting, and flaring). In many industries, including petroleum refineries, the largest source of onsite CO_2 emissions is often fossil fuel combustion, which is covered in Section 3.1 of this chapter.

Assoc Gas Flaring	0.5	0.4	0.7	1.0	1.7	1.9	1.0
Other Sources	7.8	3.5	3.6	3.2	3.2	4.5	3.0
Crude Oil Transportation	**0.2**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Refining	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.9**	**0.8**
Total	**47.8**	**41.4**	**40.4**	**40.5**	**38.6**	**40.4**	**40.2**

Note: Totals may not sum due to independent rounding.

Table 3-43: CH_4 Emissions from Petroleum Systems (kt CH_4)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	**154**	**211**	**22**	**17**	**20**	**16**	**12**
Production	**1,725**	**1,408**	**1,552**	**1,562**	**1,484**	**1,553**	**1,557**
Pneumatic Controllers	736	709	822	835	727	732	854
Offshore Production	353	259	204	204	196	196	193
Equipment Leaks	82	86	102	100	99	98	95
Gas Engines	82	71	90	89	92	94	89
Produced Water	91	62	81	84	93	98	89
Chemical Injection Pumps	47	68	82	81	80	79	76
Assoc Gas Flaring	20	14	29	38	68	77	42
Other Sources	313	139	142	130	129	179	120
Crude Oil Transportation	**7**	**5**	**8**	**8**	**8**	**9**	**9**
Refining	**27**	**31**	**33**	**34**	**31**	**36**	**31**
Total	**1,912**	**1,655**	**1,616**	**1,621**	**1,544**	**1,615**	**1,609**

Note: Totals may not sum due to independent rounding.

Table 3-44: CO_2 Emissions from Petroleum Systems (MMT CO_2)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	0.4	0.4	1.4	1.9	3.2	2.4	0.9
Production	6.0	7.9	16.6	19.4	30.3	39.2	25.0
Transportation	+	+	+	+	+	+	+
Crude Refining	3.3	3.7	4.0	3.7	3.8	5.1	4.3
Total	**9.6**	**12.0**	**21.9**	**25.0**	**37.3**	**46.7**	**30.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-45: CO_2 Emissions from Petroleum Systems (kt CO_2)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	360	392	1,373	1,852	3,189	2,418	860
Production	5,955	7,874	16,555	19,449	30,296	39,187	24,969
Transportation	0.9	0.7	1.1	1.1	1.2	1.3	1.2
Crude Refining	3,284	3,728	3,994	3,725	3,820	5,080	4,326
Total	**9,600**	**11,994**	**21,922**	**25,027**	**37,306**	**46,686**	**30,156**

Note: Totals may not sum due to independent rounding.

Table 3-46: N_2O Emissions from Petroleum Systems (Metric Tons CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	179	193	700	811	1,503	1,017	419
Production	5,518	6,145	14,370	15,069	28,724	29,734	24,386
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	9,130	10,363	11,582	10,801	10,786	14,905	12,730
Total	**14,827**	**16,702**	**26,652**	**26,680**	**41,012**	**45,656**	**37,534**

NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Table 3-47: N_2O Emissions from Petroleum Systems (Metric Tons N_2O)

Activity	1990	2005	2016	2017	2018	2019	2020
Exploration	0.6	0.6	2.3	2.7	5.0	3.4	1.4
Production	18.5	20.6	48.2	50.6	96.4	99.8	81.8
Transportation	NE	NE	NE	NE	NE	NE	NE
Crude Refining	30.6	34.8	38.9	36.2	36.2	50.0	42.7
Total	**49.8**	**56.0**	**89.4**	**89.5**	**137.6**	**153.2**	**126.0**

NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.5 for the full time series of emissions data, activity data, emission factors, and additional information on methods and data sources.

Petroleum systems includes emission estimates for activities occurring in petroleum systems from the oil wellhead through crude oil refining, including activities for crude oil exploration, production field operations, crude oil transportation activities, and refining operations. Generally, emissions are estimated for each activity by multiplying emission factors (e.g., emission rate per equipment or per activity) by corresponding activity data (e.g., equipment count or frequency of activity). Certain sources within petroleum refineries are developed using an IPCC Tier 3 approach (i.e., all refineries in the nation report facility-level emissions data to the GHGRP, which are included directly in the national emissions estimates here). Other estimates are developed with a Tier 2 approach. Tier 1 approaches are not used.

EPA received stakeholder feedback on updates in the Inventory through EPA's stakeholder process on oil and gas in the Inventory. Stakeholder feedback is noted below in Recalculations Discussion and Planned Improvements. More information on the stakeholder process can be found online.[72]

Emission Factors. Key references for emission factors include *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (GRI/EPA 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997)*, Global Emissions of Methane from Petroleum Sources* (API 1992), consensus of industry peer review panels, Bureau of Ocean Energy Management (BOEM) reports, *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017), and analysis of GHGRP data (EPA 2021).

Emission factors for hydraulically fractured (HF) oil well completions and workovers (in four control categories) were developed using EPA's GHGRP data; year-specific data were used to calculate emission factors from 2016-forward and the year 2016 emission factors were applied to all prior years in the time series. The emission factors for all years for pneumatic controllers and chemical injection pumps were developed using GHGRP data for reporting year 2014. The emission factors for tanks, well testing, and associated gas venting and flaring were developed using year-specific GHGRP data for years 2015 forward; earlier years in the time series use 2015 emission factors. For miscellaneous production flaring, year-specific emission factors were developed for years 2015 forward from GHGRP data, an emission factor of 0 (assumption of no flaring) was assumed for 1990 through 1992, and linear interpolation was applied to develop emission factors for 1993 through 2014. For more information, please see memoranda available online.[73] For offshore oil production, emission factors were calculated using BOEM data for offshore facilities in federal waters of the Gulf of Mexico (and these data were also

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[72] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

[73] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

applied to facilities located in state waters of the Gulf of Mexico) and GHGRP data for offshore facilities off the coasts of California and Alaska. For many other sources, emission factors were held constant for the period 1990 through 2020, and trends in emissions reflect changes in activity levels. Emission factors from EPA 1999 are used for all other production and transportation activities.

For associated gas venting and flaring and miscellaneous production flaring, emission factors were developed on a production basis (i.e., emissions per unit oil produced). Additionally, for these two sources, basin-specific activity and emission factors were developed for each basin that in any year from 2011 forward contributed at least 10 percent of total source emissions (on a CO_2 Eq. basis) in the GHGRP. For associated gas venting and flaring, basin-specific factors were developed for four basins: Williston, Permian, Gulf Coast, and Anadarko. For miscellaneous production flaring, basin-specific factors were developed for three basins: Williston, Permian, and Gulf Coast. For each source, data from all other basins were combined, and activity and emission factors were developed for the other basins as a single group.

For the exploration and production segments, in general, CO_2 emissions for each source were estimated with GHGRP data or by multiplying CO_2 content factors by the corresponding CH_4 data, as the CO_2 content of gas relates to its CH_4 content. Sources with CO_2 emission estimates calculated using GHGRP data include HF completions and workovers, associated gas venting and flaring, tanks, well testing, pneumatic controllers, chemical injection pumps, miscellaneous production flaring, and certain offshore production facilities (those located off the coasts of California and Alaska). For these sources, CO_2 was calculated using the same methods as used for CH_4. Carbon dioxide emission factors for offshore oil production in the Gulf of Mexico were derived using data from BOEM, following the same methods as used for CH_4 estimates. For other sources, the production field operations emission factors for CO_2 are generally estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in produced associated gas.

For the exploration and production segments, N_2O emissions were estimated for flaring sources using GHGRP or BOEM OGOR-B data and the same method used for CO_2. Sources with N_2O emissions in the exploration segment include well testing and HF completions with flaring. Sources with N_2O emissions in the production segment include associated gas flaring, tank flaring, miscellaneous production flaring, HF workovers with flaring, and flaring from offshore production sources.

For crude oil transportation, emission factors for CH_4 were largely developed using data from EPA (1997), API (1992), and EPA (1999). Emission factors for CO_2 were estimated by multiplying the CH_4 emission factors by a conversion factor, which is the ratio of CO_2 content and CH_4 content in whole crude post-separator.

For petroleum refining activities, year-specific emissions from 2010 forward were directly obtained from EPA's GHGRP. All U.S. refineries have been required to report CH_4, CO_2, and N_2O emissions for all major activities starting with emissions that occurred in 2010. The reported total CH_4, CO_2, and N_2O emissions for each activity was used for the emissions in each year from 2010 forward. To estimate emissions for 1990 to 2009, the 2010 to 2013 emissions data from GHGRP along with the refinery feed data for 2010 to 2013 were used to derive CH_4 and CO_2 emission factors (i.e., sum of activity emissions/sum of refinery feed) and 2010 to 2017 data were used to derive N_2O emission factors; these emission factors were then applied to the annual refinery feed in years 1990 to 2009. GHGRP delayed coker CH_4 emissions for 2010 through 2017 were increased using the ratio of certain reported emissions for 2018 to 2017, to account for a more accurate GHGRP calculation methodology that was implemented starting in reporting year 2018.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5.

Activity Data. References for activity data include Enverus data (Enverus 2021), Energy Information Administration (EIA) reports, *Methane Emissions from the Natural Gas Industry by the Gas Research Institute and EPA* (EPA/GRI 1996), *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999), consensus of industry peer review panels, BOEM reports, the Oil & Gas Journal, the Interstate Oil and Gas Compact Commission, the United States Army Corps of Engineers, and analysis of GHGRP data (EPA 2021).

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed to estimate values, consistent with IPCC good practice. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA/GRI (1996) and/or GHGRP data. In some cases, activity data are developed by interpolating between recent data points (such as from GHGRP) and earlier data points, such as from EPA/GRI (1996). Lastly, in limited instances the previous year's data were used if current year data were not yet available.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.5. The United States reports data to the UNFCCC using this Inventory report along with Common Reporting Format (CRF) tables. This note is provided for those reviewing the CRF tables: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRF table 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

As noted above, EPA's GHGRP data, available starting in 2010 for refineries and in 2011 for other sources, have improved estimates of emissions from petroleum systems. Many of the previously available datasets were collected in the 1990s. To develop a consistent time series for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2009 or 2014 by interpolating activity data or emission factors or both between 1992 (when GRI/EPA data are available) and 2010 or 2015 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For information on other sources, please see the Methodology Discussion above and Annex 3.5.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize uncertainty for petroleum systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates*.[74]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from petroleum systems for the current Inventory. For the CH_4 uncertainty analysis, EPA focused on the six highest methane-emitting sources for the year 2020, which together emitted 76 percent of methane from petroleum systems in 2020, and extrapolated the estimated uncertainty for the remaining sources For the CO_2 uncertainty analysis, EPA focused on the 3 highest-emitting sources for the year 2020 which together emitted 80 percent of CO_2 from petroleum systems in 2020, and extrapolated the estimated uncertainty for the remaining sources. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future Inventories.

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[74] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2020, using the recommended IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-48. Petroleum systems CH_4 emissions in 2020 were estimated to be between 29.0 and 53.1 MMT CO_2 Eq., while CO_2 emissions were estimated to be between 23.5 and 38.0 MMT CO_2 Eq. at a 95 percent confidence level. Petroleum systems N_2O emissions in 2020 were estimated to be between 0.03 and 0.05 MMT CO_2 Eq. at a 95 percent confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, associated gas venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., reduced emissions completions were not used early in the time series).

Table 3-48: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Petroleum Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petroleum Systems	CH_4	40.2	29.0	53.1	-28%	+32%
Petroleum Systems	CO_2	30.2	23.5	38.0	-22%	+26%
Petroleum Systems	N_2O	0.04	0.03	0.05	-22%	+26%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2020 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

The petroleum systems emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the emission calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[75]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current Inventory. EPA held stakeholder webinars on greenhouse gas data for oil and gas in September and November of 2021. EPA released memos detailing updates under consideration and requesting stakeholder feedback. Stakeholder feedback received through these processes is discussed in the Recalculations Discussion and Planned Improvements sections below.

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[75] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities, processes, and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed, and in many cases, incorporated data from these data sources. The second type of study can provide general indications on potential over- and under-estimates.

A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the Inventory and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level Inventory with measurement results that may be at other spatial and temporal scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[76] The gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[77] An updated version of the gridded inventory is being developed and will improve efforts to compare results of the inventory with atmospheric studies.

As discussed above, refinery emissions are quantified by using the total emissions reported to GHGRP for the refinery emission categories included in Petroleum Systems. Subpart Y has provisions that refineries are not required to report under Subpart Y if their emissions fall below certain thresholds. Each year, a review is conducted to determine whether an adjustment is needed to the Inventory emissions to include emissions from refineries that stopped reporting to the GHGRP. Based on the review of the most recent GHGRP data, EPA identified a refinery last reported annual emissions data to the GHGRP for reporting year 2012, due to meeting the criteria for cessation of reporting. EPA used the 2012 reported emissions for the refinery as proxy to gap fill annual emissions for 2013 through 2020 for this refinery.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, stakeholder feedback on updates under consideration, and new studies.

EPA did not make methodological updates for Petroleum Systems emission sources for the current Inventory. However, for certain sources, CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2019 to the current (recalculated) estimate for 2019. The emissions changes were mostly due to GHGRP data submission revisions and Enverus well count updates. These sources are discussed below and include hydraulically fractured oil well completions, associated gas venting and flaring, production storage tanks, pneumatic controllers, chemical injection pumps, gas engines, produced water, offshore production, and refineries.

The combined impact of revisions to 2019 petroleum systems CH_4 emission estimates, compared to the previous Inventory, is an increase from 39.3 to 40.4 MMT CO_2 Eq. (1.1 MMT CO_2 Eq., or 3 percent). The recalculations resulted in an average increase in CH_4 emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 1.5 MMT CO_2 Eq., or 4 percent, with the largest increase being in the estimate for 2012 (3.4 MMT CO_2 Eq. or 8 percent) primarily due to the recalculations for hydraulically fractured oil well completions.

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[76] See https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions.

[77] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

The combined impact of revisions to 2019 petroleum systems CO_2 emission estimates, compared to the previous Inventory, is a decrease from 47.3 to 46.7 MMT CO_2 (0.58 MMT CO_2, or 1 percent). The recalculations resulted in an average decrease in emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 0.02 MMT CO_2 Eq., or 0.4 percent with the largest changes being for 2019 primarily due to the recalculations for associated gas flaring.

The combined impact of revisions to 2019 petroleum systems N_2O emission estimates, compared to the previous Inventory, is a decrease of 0.001 MMT CO_2, Eq. or 3 percent. The emission changes were primarily driven by reduction in flaring emissions from associated gas and offshore production flaring due to GHGRP data submission revisions. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 0.002 MMT CO_2 Eq., or 9 percent.

In Table 3-49 and Table 3-50 below are categories in Petroleum Systems with updated methodologies or with recalculations resulting in a change of greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2019 to the current (recalculated) estimate for 2019. For more information, please see the discussion below.

Table 3-49: Recalculations of CO_2 in Petroleum Systems (MMT CO_2)

Segment/Source	*Previous Estimate Year 2019, 2021 Inventory*	Current Estimate Year 2019, 2022 Inventory	Current Estimate Year 2020, 2022 Inventory
Exploration	***2.1***	**2.4**	**0.9**
HF Oil Well Completions	*2.1*	2.4	0.9
Production	***40.2***	**39.2**	**25.0**
Tanks	*6.1*	6.7	6.5
Associated Gas Flaring	*25.4*	23.7	13.0
Transportation	***+***	**+**	**+**
Refining	***5.0***	**5.1**	**4.3**
Petroleum Systems Total	***47.3***	**46.7**	**30.2**

+ Does not exceed 0.05 MMT CO_2.

Table 3-50: Recalculations of CH_4 in Petroleum Systems (MMT CO_2 Eq.)

Segment/Source	*Previous Estimate Year 2019, 2021 Inventory*	Current Estimate Year *2019*, 2022 Inventory	Current Estimate Year 2020, 2022 Inventory
Exploration	***0.3***	**0.4**	**0.3**
HF Oil Well Completions	*0.2*	0.4	0.3
Production	***35.7***	**38.8**	**38.9**
Produced Water	*2.1*	2.4	2.2
Tanks	*1.5*	0.9	0.7
Pneumatic Controllers	*17.5*	18.3	21.3
Associated Gas Flaring	*2.0*	1.9	1.0
Associated Gas Venting	*1.1*	1.7	0.6
Chemical Injection Pumps	*1.9*	2.0	1.9
Offshore Production	*5.0*	4.9	4.8
Gas Engines	*2.4*	2.3	2.2
Transportation	***0.2***	**0.2**	**0.2**
Refining	***0.9***	**0.9**	**0.8**
Petroleum Systems Total	***39.3***	**40.4**	**40.2**

Exploration

HF Oil Well Completions (Recalculation with Updated Data)

HF oil well completion CO_2 emissions increased by an average of 24 percent across the time series and increased by 16 percent in 2019, compared the to the previous Inventory. The emissions changes were due to GHGRP data submission revisions and updated Enverus well completion counts.

Table 3-51: HF Oil Well Completions National CO_2 Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
HF Completions: Non-REC with Venting	3	4	+	+	+	+	+
HF Completions: Non-REC with Flaring	115	163	280	430	644	925	386
HF Completions: REC with Venting	NO	NO	+	+	+	+	+
HF Completions: REC with Flaring	NO	NO	1,053	1,385	2,512	1,489	472
Total Emissions	**119**	**168**	**1,333**	**1,815**	**3,155**	**2,414**	**858**
Previous Estimate	*91*	*144*	*1,174*	*1,664*	*2,874*	*2,078*	*NA*

+ Does not exceed 0.5 kt CO_2.
NA (Not Applicable)
NO (Not Occurring)

HF oil well completion CH_4 emissions increased by an average of 27 percent across the time series and increased by 53 percent in 2019, compared the to the previous Inventory. The emissions changes were due to GHGRP data submission revisions and updated Enverus well completion counts.

Table 3-52: HF Oil Well Completions National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
HF Completions: Non-REC with Venting	142,812	202,077	8,034	2,882	169	805	819
HF Completions: Non-REC with Flaring	492	696	1,195	1,877	2,690	3,059	2,018
HF Completions: REC with Venting	NO	NO	3,695	4,127	4,892	5,071	5,716
HF Completions: REC with Flaring	NO	NO	5,584	6,499	10,362	6,127	2,024
Total Emissions	**143,304**	**202,773**	**18,507**	**15,386**	**18,113**	**15,062**	**10,576**
Previous Estimate	*109,658*	*173,537*	*15,039*	*12,326*	*14,187*	*9,871*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Production

Produced Water (Recalculation with Updated Data)

Produced water CH_4 emissions increased by an average of 2 percent across the time series and increased by 15 percent in 2019, compared the to the previous Inventory. The emissions changes were primarily due to incorporating year-specific produced water volumes from Enverus and supplemented with updated data from the NEI's O&G Tool for 6 states (IL, IN, KS, OK, PA, and WV).

Table 3-53: Produced Water National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Low Pressure Oil Wells	20,273	13,855	18,073	18,661	20,599	21,680	19,658
Regular Pressure Oil Wells	71,118	48,603	63,403	65,464	72,263	76,055	68,964
Total	**91,391**	**62,458**	**81,477**	**84,125**	**92,863**	**97,735**	**88,622**
Previous Estimate	*91,478*	*62,184*	*77,278*	*78,739*	*82,806*	*84,726*	*NA*

NA (Not Applicable)

Tanks (Recalculation with Updated Data)

Tank CO_2 emissions estimates decreased by an average of 0.2 percent across the 1990 to 2019 time series and increased by 10 percent in 2019, compared to the previous inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-54: Tanks National CO_2 Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Large Tanks w/Flares	NO	2,440	4,441	4,247	6,130	6,625	6,486
Large Tanks w/VRU	NO	5	3	4	4	6	1
Large Tanks w/o Control	24	6	5	4	5	5	4
Small Tanks w/Flares	NO	2	10	11	8	9	13
Small Tanks w/o Flares	6	3	4	4	4	4	5
Malfunctioning Separator Dump Valves	85	50	31	43	38	33	28
Total Emissions	**115**	**2,505**	**4,494**	**4,313**	**6,189**	**6,682**	**6,537**
Previous Estimate	*116*	*2,517*	*4,546*	*4,364*	*6,278*	*6,098*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Tank CH_4 emissions estimates decreased by an average of 2 percent across the 1990 to 2019 time series and decreased by 41 percent in 2019, compared to the previous inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-55: Tanks National CH_4 Emissions (MT CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Large Tanks w/Flares	NO	2,303	3,994	5,310	6,879	4,324	4,268
Large Tanks w/VRU	NO	1,116	14,369	9,058	2,574	2,430	1,109
Large Tanks w/o Control	210,278	52,435	48,888	39,930	44,185	25,454	20,746
Small Tanks w/Flares	NO	15	17	63	22	29	33
Small Tanks w/o Flares	4,206	2,009	2,551	2,399	2,710	2,493	3,014
Malfunctioning Separator Dump Valves	3,935	2,308	6,029	4,338	1,043	536	443
Total Emissions	**218,419**	**60,186**	**75,848**	**61,098**	**57,412**	**35,266**	**29,613**
Previous Estimate	*219,476*	*60,489*	*76,086*	*61,658*	*58,848*	*59,965*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Pneumatic Controllers (Recalculation with Updated Data)

Pneumatic controller CH_4 emission estimates increased by an average of 3 percent across the 1990 to 2019 time series and increased by 5 percent in 2019, compared to the previous Inventory. The emission changes were due to GHGRP data submission revisions and updated Enverus well counts.

Table 3-56: Pneumatic Controller National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
High Bleed	689,395	423,219	81,038	52,508	39,530	45,196	43,014
Low Bleed	47,052	44,322	17,302	19,395	30,184	39,497	33,783
Intermittent Bleed	NO	241,140	724,015	763,226	657,651	647,399	776,765
Total Emissions	**736,447**	**708,680**	**822,355**	**835,129**	**727,365**	**732,092**	**853,562**
Previous Estimate	*792,075*	*672,769*	*785,023*	*799,496*	*693,976*	*699,488*	*NA*

NA (Not Applicable)

Associated Gas Flaring (Recalculation with Updated Data)

Associated gas flaring CO_2 emission estimates decreased by an average of 3 percent across the time series and decreased by 6 percent in 2019 in the current Inventory, compared to the previous Inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-57: Associated Gas Flaring National CO_2 Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
220 - Gulf Coast Basin (LA, TX)	225	124	405	749	651	713	798
360 - Anadarko Basin	102	63	1	62	79	18	10
395 - Williston Basin	969	1,243	6,090	6,909	11,140	14,762	8,052
430 - Permian Basin	2,844	1,971	2,215	3,141	6,711	7,227	3,558
"Other" Basins	944	507	322	384	624	990	624
Total Emissions	**5,084**	**3,908**	**9,033**	**11,245**	**19,206**	**23,710**	**13,041**
220 - Gulf Coast Basin (LA, TX)	*227*	*121*	*404*	*744*	*643*	*584*	*NA*
360 - Anadarko Basin	*108*	*66*	*1*	*64*	*82*	*18*	*NA*
395 - Williston Basin	*987*	*1,263*	*6,091*	*6,908*	*11,140*	*16,572*	*NA*
430 - Permian Basin	*2,983*	*2,056*	*2,261*	*3,209*	*6,782*	*7,161*	*NA*
"Other" Basins	*935*	*505*	*324*	*387*	*641*	*1,021*	*NA*
Previous Estimate	*5,241*	*4,011*	*9,081*	*11,313*	*19,287*	*25,356*	*NA*

NA (Not Applicable)

Associated gas flaring CH_4 emission estimates decreased by an average of 4 percent across the time series and decreased by 5 percent in 2019 in the current Inventory, compared to the previous Inventory. The emission changes were due to GHGRP data submission revisions.

Table 3-58: Associated Gas Flaring National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
220 - Gulf Coast Basin (LA, TX)	886	490	1,576	2,949	2,480	2,995	3,710
360 - Anadarko Basin	447	274	4	268	348	88	21
395 - Williston Basin	2,665	3,419	16,945	20,707	37,756	43,637	22,954
430 - Permian Basin	11,263	7,805	8,793	12,912	25,236	27,194	12,854
"Other" Basins	4,369	2,347	1,185	1,278	1,881	3,507	2,312
Total Emissions	**19,630**	**14,335**	**28,503**	**38,115**	**67,701**	**77,422**	**41,850**
220 - Gulf Coast Basin (LA, TX)	*896*	*479*	*1,572*	*2,936*	*2,448*	*2,626*	*NA*
360 - Anadarko Basin	*472*	*288*	*4*	*277*	*358*	*87*	*NA*
395 - Williston Basin	*2,931*	*3,750*	*16,948*	*20,707*	*37,754*	*48,453*	*NA*
430 - Permian Basin	*11,815*	*8,143*	*8,972*	*13,189*	*25,511*	*27,016*	*NA*
"Other" Basins	*4,328*	*2,335*	*1,193*	*1,290*	*1,932*	*3,614*	*NA*
Previous Estimate	*20,441*	*14,995*	*28,689*	*38,399*	*68,004*	*81,797*	*NA*

NA (Not Applicable)

Associated Gas Venting (Recalculation with Updated Data)

Associated gas venting CH_4 emission estimates increased by an average of 1 percent across the 1990 to 2019 time series in the current Inventory, compared to the previous Inventory. The CH_4 estimates increased by 63 percent in 2019, primarily due to Permian Basin data. The changes were due to GHGRP data submission revisions.

Table 3-59: Associated Gas Venting National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
220 - Gulf Coast Basin (LA, TX)	475	263	2,455	580	957	7,621	1,288
360 - Anadarko Basin	811	497	782	4,585	318	596	1,700
395 - Williston Basin	207	265	1,479	628	575	4,044	341

430 - Permian Basin	4,041	2,800	8,060	9,635	9,505	54,192	18,269
"Other" Basins	15,763	8,468	5,071	3,472	1,739	2,082	1,919
Total Emissions	**21,297**	**12,295**	**17,847**	**18,899**	**13,093**	**68,535**	**23,517**
220 - Gulf Coast Basin (LA, TX)	*480*	*257*	*2,449*	*579*	*944*	*18,139*	*NA*
360 - Anadarko Basin	*858*	*524*	*813*	*4,728*	*328*	*590*	*NA*
395 - Williston Basin	*211*	*269*	*1,479*	*628*	*575*	*10,855*	*NA*
430 - Permian Basin	*4,239*	*2,922*	*8,224*	*9,842*	*9,647*	*8,637*	*NA*
"Other" Basins	*15,613*	*8,424*	*5,104*	*3,503*	*1,788*	*3,830*	*NA*
Previous Estimate	*21,401*	*12,396*	*18,069*	*19,280*	*13,282*	*42,051*	*NA*

NA (Not Applicable)

Chemical Injection Pumps (Recalculation with Updated Data)

Chemical injection pump CH_4 emission estimates increased by an average of 3 percent across the time series and increased by 5 percent in 2019, compared to the previous Inventory. The emission changes were due to updated Enverus well counts.

Table 3-60: Chemical Injection Pump National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Chemical Injection Pump	46,758	67,685	81,936	80,728	79,793	79,128	76,284
Previous Estimate	*50,806*	*64,259*	*78,351*	*77,061*	*76,014*	*75,182*	*NA*

NA (Not Applicable)

Offshore Production (Recalculation with Updated Data)

Offshore production CH_4 emission estimates decreased by an average of 2 percent across the time series and decreased by 3 percent in 2019, compared to the previous Inventory. The emission changes were due to updated offshore complex counts.

Table 3-61: Offshore Production National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
GOM Federal Waters	302,936	219,285	189,595	186,606	182,662	181,724	178,496
GOM State Waters	5,657	665	108	96	60	71	61
Pacific Waters	22,609	17,659	5,008	5,052	3,794	3,370	4,262
Alaska State Waters	21,936	21,191	9,680	12,163	9,834	10,461	10,123
Total Emissions	**353,138**	**258,801**	**204,391**	**203,917**	**196,349**	**195,626**	**192,943**
Previous Estimate	*373,650*	*260,994*	*205,958*	*205,008*	*199,063*	*200,720*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engine (combustion slip) CH_4 emission estimates decreased by an average of 3 percent across the time series and decreased by 4 percent in 2019, compared to the previous Inventory. The emission changes were due to updated Enverus well counts. Even though the well counts have increased across the time series, the 2019 gas engine estimates are calculated using the ratio of 2019 to 1993 well counts. Since the 1993 well counts show a larger increase (12 percent) compared to the 2019 well counts (5 percent), the gas engine estimates increased.

Table 3-62: Gas Engine National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Total Gas Engine Emissions	**81,916**	**71,348**	**89,735**	**89,471**	**91,693**	**93,556**	**89,471**
Previous Estimate	*87,854*	*73,659*	*94,771*	*94,311*	*96,338*	*97,828*	*NA*

NA (Not Applicable)

Well Counts (Recalculation with Updated Data)

EPA uses annual producing oil well counts as an input for estimates of emissions from multiple sources in the Inventory, including exploration well testing, pneumatic controllers, chemical injection pumps, well workovers, and equipment leaks. Annual well count data are obtained from Enverus for the entire time series during each Inventory cycle. In addition, well counts for Illinois and Indiana were fully incorporated for this Inventory, based on information available from state agencies or from EIA. Enverus does not contain well count data for Illinois and Indiana. There are an average of approximately 25,200 oil wells for Illinois and 15,600 oil wells for Indiana, across the time series. Annual well counts increased by an average of 7 percent across the 1990 to 2019 time series and increased by 5 percent in 2019, compared to the previous Inventory.

Table 3-63: National Oil Well Counts

Source	1990		2005		2016	2017	2018	2019	2020
Oil Wells	520,364		482,007		568,640	560,258	553,769	549,153	529,419
Previous Estimate	*506,730*		*447,683*		*543,759*	*534,806*	*527,544*	*521,771*	*NA*

NA (Not Applicable)

In January 2022, EIA released an updated time series of national oil and gas well counts (covering 2000 through 2020). EIA estimates 936,984 total wells for year 2020. EPA's total well count for 2020 is 939,665. EPA well counts are higher due to the inclusion of wells for Illinois and Indiana in the current Inventory. EIA does not include wells for these two states. If these states are excluded from the well count comparison (i.e., well counts are compared only for the states that are in both EIA and EPA datasets), EPA's well counts are about 2 percent lower than EIA's in 2020, in part due to well definitions. EIA's well counts include side tracks (i.e., secondary wellbore away from original wellbore in order to bypass unusable formation, explore nearby formations, or other reasons), completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. Note, EPA and EIA use a different threshold for distinguishing between oil versus gas wells (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells (e.g., 44 percent versus EPA's 56 percent in 2020) and a higher fraction of gas wells (e.g., 56 percent versus EPA's 44 percent in 2020) than EPA.

Transportation

Recalculations for the transportation segment have resulted in an average decrease in calculated CH_4 and CO_2 emissions over the time series from this segment of less than 0.2 percent, compared to the previous Inventory.

Refining

Recalculations due to resubmitted GHGRP data in the refining segment have resulted in an average decrease in calculated CH_4 emissions over the time series from this segment of less than 0.1 percent and increased by 0.8 percent in 2019 in the current Inventory, compared to the previous Inventory. Additionally, EPA identified one refinery that stopped reporting to GHGRP starting in 2013 due to meeting the criteria for cessation of reporting. EPA used the refinery's 2012 reported annual emissions to gap fill for 2013 through 2020. This resulted in a very minor increase in refinery CH_4 emissions compared to the previous Inventory (0.02 percent).

Refining CO_2 emission estimates increased by an average of 0.1 percent across the time series and increased by 1 percent in 2019 in the current Inventory, compared to the previous Inventory.

Table 3-64: Refining National CO_2 Emissions (kt CO_2)

Source	1990		2005		2016	2017	2018	2019	2020
Refining	3,284		3,728		3,994	3,725	3,820	5,080	4,326
Previous Estimate	*3,284*		*3,728*		*3,991*	*3,714*	*3,735*	*5,019*	*NA*

NA (Not Applicable)

Planned Improvements

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the Methane Challenge Program on an ongoing basis, which may be used to confirm or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory. EPA will also continue to assess studies that include and compare both top-down and bottom-up estimates, and which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, in recent years, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank measurements and tank and flaring malfunction and control efficiency data.
- Improved equipment leak data (activity and emissions).
- Activity data and emissions data for production facilities that do not report to GHGRP.
- Associated gas venting and flaring data on practices from 1990 through 2010.
- Onshore mud degassing.
- Refineries emissions data.
- Anomalous leak events information throughout the time series and for future years.

EPA received stakeholder feedback through comments on the public review draft of the current Inventory. Several stakeholders asserted that methane emissions are undercounted in petroleum systems. A stakeholder comment suggested developing the inventory using a strategy that combines information from satellites, aircraft-based instruments, and ground-based sensors. Stakeholder feedback on the public review draft recommended use of updated emission factors for pneumatic controllers.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

Box 3-6: Carbon Dioxide Transport, Injection, and Geological Storage

Carbon dioxide is produced, captured, transported, and used for Enhanced Oil Recovery (EOR) as well as commercial and non-EOR industrial applications, or is stored geologically. This CO_2 is produced from both naturally-occurring CO_2 reservoirs and from industrial sources such as natural gas processing plants and ammonia plants. In the Inventory, emissions of CO_2 from naturally-occurring CO_2 reservoirs are estimated based on the specific application.

In the Inventory, CO_2 that is used in non-EOR industrial and commercial applications (e.g., food processing, chemical production) is assumed to be emitted to the atmosphere during its industrial use. These emissions are discussed in the Carbon Dioxide Consumption section, 4.15.

For EOR CO_2, as noted in the *2006 IPCC Guidelines*, "At the Tier 1 or 2 methodology levels [EOR CO_2 is] indistinguishable from fugitive greenhouse gas emissions by the associated oil and gas activities." In the U.S. estimates for oil and gas fugitive emissions, the Tier 2 emission factors for CO_2 include CO_2 that was originally injected and is emitted along with other gas from leak, venting, and flaring pathways, as measurement data used to develop those factors would not be able to distinguish between CO_2 from EOR and CO_2 occurring in the produced natural gas. Therefore, EOR CO_2 emitted through those pathways is included in CO_2 estimates in 1B2.

IPCC includes methodological guidance to estimate emissions from the capture, transport, injection, and geological storage of CO_2. The methodology is based on the principle that the carbon capture and storage system should be handled in a complete and consistent manner across the entire Energy sector. The approach accounts for CO_2 captured at natural and industrial sites as well as emissions from capture, transport, and use. For storage specifically, a Tier 3 methodology is outlined for estimating and reporting emissions based on site-specific evaluations. However, IPCC (IPCC 2006) notes that if a national regulatory process exists, emissions information available through that process may support development of CO_2 emission estimates for geologic storage.

In the United States, facilities that produce CO_2 for various end-use applications (including capture facilities such as acid gas removal plants and ammonia plants), importers of CO_2, exporters of CO_2, facilities that conduct geologic sequestration of CO_2, and facilities that inject CO_2 underground, are required to report greenhouse gas data annually to EPA through its GHGRP. Facilities reporting geologic sequestration of CO_2 to the GHGRP develop and implement an EPA-approved site-specific monitoring, reporting and verification plan, and report the amount of CO_2 sequestered using a mass balance approach.

GHGRP data relevant for this inventory estimate consists of national-level annual quantities of CO_2 captured and extracted for EOR applications for 2010 to 2020 and data reported for geologic sequestration from 2016 to 2020.

The amount of CO_2 captured and extracted from natural and industrial sites for EOR applications in 2020 is 35,210 kt (35.2 MMT CO_2 Eq.) (see 6). The quantity of CO_2 captured and extracted is noted here for information purposes only; CO_2 captured and extracted from industrial and commercial processes is generally assumed to be emitted and included in emissions totals from those processes, and EPA received a public review comment in support of updating the approach.

Table 3-65: Quantity of CO_2 Captured and Extracted for EOR Operations (kt CO_2)

Stage	2016	2017	2018	2019	2020
Quantity of CO_2 Captured and Extracted for EOR Operations	46,700	49,600	48,400	52,100	35,210

Several facilities are reporting under GHGRP subpart RR (Geologic Sequestration of Carbon Dioxide). See Table 3-66 for the number of facilities reporting under subpart RR, the reported CO_2 sequestered in subsurface geologic formations in each year, and of the quantity of CO_2 emitted from equipment leaks in each year. The quantity of CO_2 sequestered and emitted is noted here for information purposes only; EPA is considering updates to its approach in the Inventory for this source for future Inventories.

Table 3-66: Geologic Sequestration Information Reported Under GHGRP Subpart RR

Stage	2016	2017	2018	2019	2020
Number of Reporting Facilities	1	3	5	5	6
Reported Annual CO_2 Sequestered (kt)	3,091	5,958	7,662	8,332	6,765
Reported Annual CO_2 Emissions from Equipment Leaks (kt)	10	10	11	16	74

3.7 Natural Gas Systems (CRF Source Category 1B2b)

The U.S. natural gas system encompasses hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. This IPCC category (1B2b) is for fugitive emissions from natural gas systems, which per IPCC guidelines include emissions from leaks, venting, and flaring. Total greenhouse gas emissions (CH_4, CO_2, and N_2O) from natural gas systems in 2020 were 200.3 MMT CO_2 Eq., a decrease of 12 percent from 1990 and a decrease of 5 percent from 2019, both primarily due to decreases in CH_4

emissions. From 2010, emissions increased by 4 percent, primarily due to increases in CO_2 emissions. National total dry gas production in the United States increased by 88 percent from 1990 to 2020, decreased by 1 percent from 2019 to 2020, and increased by 62 percent from 2009 to 2020. Of the overall greenhouse gas emissions (200.3 MMT CO_2 Eq.), 82 percent are CH_4 emissions (164.9 MMT CO_2 Eq.), 18 percent are CO_2 emissions (35.4 MMT), and less than 0.01 percent are N_2O emissions (0.01 MMT CO_2 Eq.).

Overall, natural gas systems emitted 164.9 MMT CO_2 Eq. (6,596 kt CH_4) of CH_4 in 2020, a 16 percent decrease compared to 1990 emissions, and 4 percent decrease compared to 2019 emissions (see Table 3-68 and Table 3-69). For non-combustion CO_2, a total of 35.4 MMT CO_2 Eq. (35,369 kt) was emitted in 2020, a 11 percent increase compared to 1990 emissions, and a 9 percent decrease compared to 2019 levels. The 2020 N_2O emissions were estimated to be 0.01 MMT CO_2 Eq. (0.03 kt N_2O), a 105 percent increase compared to 1990 emissions, and a 15 percent decrease compared to 2019 levels.

The 1990 to 2019 emissions trend is not consistent across segments or gases. Overall, the 1990 to 2020 decrease in CH_4 emissions is due primarily to the decrease in emissions from the following segments: distribution (70 percent decrease), transmission and storage (29 percent decrease), processing (42 percent decrease), and exploration (93 percent decrease). Over the same time period, the production segment saw increased CH_4 emissions of 43 percent (with onshore production emissions increasing 24 percent, offshore production emissions decreasing 77 percent, and gathering and boosting [G&B] emissions increasing 103 percent), and post-meter emissions increasing by 58 percent. The 1990 to 2020 increase in CO_2 emissions is primarily due to an increase in CO_2 emissions in the production segment, where emissions from flaring have increased over time.

Methane and CO_2 emissions from natural gas systems include those resulting from normal operations, routine maintenance, and system upsets. Emissions from normal operations include natural gas engine and turbine uncombusted exhaust, flaring, and leak emissions from system components. Routine maintenance emissions originate from pipelines, equipment, and wells during repair and maintenance activities. Pressure surge relief systems and accidents can lead to system upset emissions. Emissions of N_2O from flaring activities are included in the Inventory, with most of the emissions occurring in the processing and production segments. Note, CO_2 emissions exclude all combustion emissions (e.g., engine combustion) except for flaring CO_2 emissions. All combustion CO_2 emissions (except for flaring) are accounted for in Section 3.1 CO_2 from Fossil Fuel Combustion.

Each year, some estimates in the Inventory are recalculated with improved methods and/or data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is representative of changes in emissions. Recalculations in natural gas systems in this year's Inventory include:

- Incorporation of an estimate for post-meter emissions
- Incorporation of estimates for large anomalous leak events
- Updated GasSTAR and Methane Challenge data
- Updated activity data for underground storage wells
- Updates to well counts using the most recent data from Enverus
- Recalculations due to Greenhouse Gas Reporting Program (GHGRP) submission revisions

The Recalculations Discussion section below provides more details on the updated methods.

Below is a characterization of the six emission subcategories of natural gas systems: exploration, production (including gathering and boosting), processing, transmission and storage, distribution, and post-meter. Each of the segments is described and the different factors affecting CH_4, CO_2, and N_2O emissions are discussed.

Exploration. Exploration includes well drilling, testing, and completions. Emissions from exploration accounted for less than 1 percent of CH_4 emissions and of CO_2 emissions from natural gas systems in 2020. Well completions accounted for approximately 90 percent of CH_4 emissions from the exploration segment in 2020, with the rest resulting from well testing and drilling. Flaring emissions account for most of the CO_2 emissions. Methane emissions from exploration decreased by 93 percent from 1990 to 2020, with the largest decreases coming from hydraulically fractured gas well completions without reduced emissions completions (RECs). Methane emissions decreased 89 percent from 2019 to 2020 due to decreases in emissions from hydraulically fractured well completions with RECs and venting. Methane emissions were highest from 2005 to 2008. Carbon dioxide emissions from exploration decreased by 68 percent from 1990 to 2020 and decreased 57 percent from 2019 to 2020 due to decreases in hydraulically fractured gas well completions. Carbon dioxide emissions were highest from 2006 to 2008. Nitrous oxide emissions decreased 87 percent from 1990 to 2020 and decreased 57 percent from 2019 to 2020.

Production (including gathering and boosting). In the production segment, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, and from well-site equipment and activities such as pneumatic controllers, tanks and separators, and liquids unloading. Gathering and boosting emission sources are included within the production sector. The gathering and boosting sources include gathering and boosting stations (with multiple emission sources on site) and gathering pipelines. The gathering and boosting stations receive natural gas from production sites and transfer it, via gathering pipelines, to transmission pipelines or processing facilities (custody transfer points are typically used to segregate sources between each segment). Boosting processes include compression, dehydration, and transport of gas to a processing facility or pipeline. Emissions from production (including gathering and boosting) accounted for 52 percent of CH_4 emissions and 22 percent of CO_2 emissions from natural gas systems in 2020. Emissions from gathering and boosting and pneumatic controllers in onshore production accounted for most of the production segment CH_4 emissions in 2020. Within gathering and boosting, the largest sources of CH_4 are compressor exhaust slip, compressor venting and leaks, and tanks. Flaring emissions account for most of the CO_2 emissions from production, with the highest emissions coming from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring. Methane emissions from production increased by 156 percent from 1990 to 2020, due primarily to increases in emissions from pneumatic controllers (due to an increase in the number of controllers, particularly in the number of intermittent bleed controllers) and increases in emissions from compressor exhaust slip in gathering and boosting. Methane emissions decreased 7 percent from 2019 to 2020 due to decreases in emissions from pneumatic controllers and from tanks in gathering and boosting. Carbon dioxide emissions from production increased by approximately a factor of 2.6 from 1990 to 2020 due to increases in emissions at flare stacks in gathering and boosting and miscellaneous onshore production flaring, and decreased 29 percent from 2019 to 2020 due primarily to decreases in emissions from flare stacks and dehydrator vents at gathering and boosting stations . Nitrous oxide emissions decreased less than 1percent from 1990 to 2020 and decreased 23 percent from 2019 to 2020. The decrease in N_2O emissions from 1990 to 2020 and from 2018 to 2020 is primarily due to decreases in emissions from flare stacks at gathering and boosting stations.

Processing. In the processing segment, natural gas liquids and various other constituents from the raw gas are removed, resulting in “pipeline quality” gas, which is injected into the transmission system. Methane emissions from compressors, including compressor seals, are the primary emission source from this stage. Most of the CO_2 emissions come from acid gas removal (AGR) units, which are designed to remove CO_2 from natural gas. Processing plants accounted for 8 percent of CH_4 emissions and 72 percent of CO_2 emissions from natural gas systems. Methane emissions from processing decreased by 42 percent from 1990 to 2020 as emissions from compressors (leaks and venting) and equipment leaks decreased; and decreased 2 percent from 2018 to 2020 due to decreased emissions from centrifugal compressors. Carbon dioxide emissions from processing decreased by 10 percent from 1990 to 2020, due to a decrease in AGR emissions, and decreased 3 percent from 2019 to 2020 due to decreased emissions from reciprocating compressors. Nitrous oxide emissions increased 39 percent from 2018 to 2019.

Transmission and Storage. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities are used to move the gas throughout the U.S. transmission system. Leak CH_4 emissions from these compressor stations and venting from pneumatic controllers account for most of the emissions from this stage. Uncombusted compressor engine exhaust and pipeline venting are also sources of CH_4 emissions from transmission. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Leak and venting emissions from compressors are the primary contributors to CH_4 emissions from storage. Emissions from liquefied natural gas (LNG) stations and terminals are also calculated under the transmission and storage segment. Methane emissions from the transmission and storage segment accounted for approximately 25 percent of emissions from natural gas systems, while CO_2 emissions from transmission and storage accounted for 6 percent of the CO_2 emissions from natural gas systems. CH_4 emissions from this source decreased by 29 percent from 1990 to 2020 due to reduced compressor station emissions (including emissions from compressors and leaks) and increased 3 percent from 2019 to 2020 due to increased emissions from transmission compressors. CO_2 emissions from transmission and storage were 11.3 times higher in 2020 than in 1990, due to increased emissions from LNG export terminals and LNG stations, and increased by 64 percent from 2019 to 2020, also due to LNG export terminals. The quantity of LNG exported from the United States increased by a factor of 45 from 1990 to 2020, and by 31 percent from 2019 to 2020. LNG emissions are about 1 percent of CH_4 and 86 percent of CO_2 emissions from transmission and storage in year 2020. Nitrous oxide emissions from transmission and storage increased by 317 percent from 1990 to 2020 and increased 70 percent from 2019 to 2020.

Distribution. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. There were 1,316,800 miles of distribution mains in 2020, an increase of 372,643 miles since 1990 (PHMSA 2021). Distribution system emissions, which accounted for 8 percent of CH_4 emissions from natural gas systems and less than 1 percent of CO_2 emissions, result mainly from leak emissions from pipelines and stations. An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced both CH_4 and CO_2 emissions from this stage, as have station upgrades at metering and regulating (M&R) stations. Distribution system CH_4 emissions in 2020 were 70 percent lower than 1990 levels and less than 1 percent lower than 2019 emissions. Distribution system CO_2 emissions in 2020 were 69 percent lower than 1990 levels and less than 1 percent lower than 2019 emissions. Annual CO_2 emissions from this segment are less than 0.1 MMT CO_2 Eq. across the time series.

Post-Meter. Post-meter includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. Leak emissions from residential appliances and industrial facilities and power plants account for the majority of post-meter CH_4 emissions. Methane emissions from the post-meter segment accounted for approximately 8 percent of emissions from natural gas systems in 2020. Post-meter CH_4 emissions increased by 58 percent from 1990 to 2020 and increased by 1 percent from 2019 to 2020, due to increases in the number of residential houses using natural gas and increased natural gas consumption at industrial facilities and power plants. CO_2 emissions from post-meter account for less than 0.01 percent of total CO_2 emissions from natural gas systems.

Total greenhouse gas emissions from the six subcategories within natural gas systems are shown in MMT CO_2 Eq. in Table 3-67. Total CH_4 emissions for these same segments of natural gas systems are shown in MMT CO_2 Eq. (Table 3-68) and kt (Table 3-69). Most emission estimates are calculated using a net emission approach. However, a few sources are still calculated with a potential emission approach. Reductions data are applied to those sources. In 2020, 2.6 MMT CO_2 Eq. CH_4 is subtracted from production segment emissions, 4.0 MMT CO_2 Eq. CH_4 is subtracted from the transmission and storage segment, and 0.1 MMT CO_2 Eq. CH_4 is subtracted from the distribution segment to calculate net emissions. More disaggregated information on potential emissions, net emissions, and reductions data is available in Annex 3.6, Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems.

Table 3-67: Total Greenhouse Gas Emissions (CH_4, CO_2, and N_2O) from Natural Gas Systems (MMT CO_2 Eq.)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	3.3	10.4	0.9	1.7	2.7	2.1	0.3
Production	64.3	87.9	97.6	99.8	102.3	103.6	94.1
Processing	49.7	30.4	33.0	34.5	35.1	39.0	37.8
Transmission and Storage	57.4	39.7	38.7	37	39.0	40.8	42.7
Distribution	45.5	25.5	14.2	14.1	14.0	13.9	13.9
Post-Meter	7.2	8.6	10.7	10.6	11.1	11.4	11.5
Total	**227.4**	**202.5**	**195.06**	**197.7**	**204.2**	**210.9**	**200.3**

Note: Totals may not sum due to independent rounding.

Table 3-68: CH_4 Emissions from Natural Gas Systems (MMT CO_2 Eq.)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	**3.0**	**9.0**	**0.7**	**1.2**	**2.3**	**1.9**	**0.2**
Production	**61.3**	**83.4**	**90.1**	**92.6**	**93.8**	**92.8**	**86.4**
Onshore Production	37.5	56.8	52.6	53.4	54.3	51.6	47.6
Gathering and Boosting	18.5	24.0	36.4	38.3	38.7	39.9	37.5
Offshore Production	4.3	1.8	0.8	0.7	0.8	0.8	1.0
Processing	**21.3**	**11.6**	**11.2**	**11.5**	**12.1**	**12.6**	**12.4**
Transmission and Storage	**57.2**	**39.5**	**38.3**	**36.5**	**38.4**	**39.6**	**40.6**
Distribution	**45.5**	**25.5**	**14.2**	**14.1**	**14.0**	**13.9**	**13.9**
Post-Meter	**7.2**	**8.6**	**10.7**	**10.6**	**11.1**	**11.4**	**11.5**
Total	**195.5**	**177.5**	**165.2**	**166.6**	**171.8**	**172.1**	**164.9**

Note: Totals may not sum due to independent rounding.

Table 3-69: CH_4 Emissions from Natural Gas Systems (kt)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	**119**	**358**	**27**	**49**	**94**	**75**	**8**
Production	**2,450**	**3,336**	**3,605**	**3,705**	**3,753**	**3,710**	**3,455**
Onshore Production	1,542	2305	2,115	2,145	2,174	2,085	1,916
Gathering and Boosting	739	958	1,457	1,533	1,548	1,595	1,500
Offshore Production	170	73	32	26	31	30	39
Processing	**853**	**463**	**447**	**460**	**483**	**505**	**494**
Transmission and Storage	**2,288**	**1,580**	**1,534**	**1,460**	**1,538**	**1,583**	**1,625**
Distribution	**1,819**	**1,018**	**569**	**564**	**559**	**555**	**554**
Post-Meter	**290**	**344**	**426**	**424**	**445**	**457**	**459**
Total	**7,819**	**7,100**	**6,609**	**6,662**	**6,871**	**6,885**	**6,596**

Note: Totals may not sum due to independent rounding.

Table 3-70: CO_2 Emissions from Natural Gas Systems (MMT)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	0.3	1.4	0.2	0.4	0.3	0.2	0.1
Production	3.0	4.5	7.4	7.2	8.5	10.9	7.7
Processing	28.3	18.8	21.8	23.0	23.0	26.4	25.5
Transmission and Storage	0.2	0.2	0.3	0.5	0.5	1.2	2.0
Distribution	0.1	+	+	+	+	+	+
Post-Meter	+	+	+	+	+	+	+
Total	**31.9**	**24.9**	**29.8**	**31.1**	**32.4**	**38.7**	**35.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 3-71: CO_2 Emissions from Natural Gas Systems (kt)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	297	1,434	190	444	336	220	95
Production	3,024	4,468	7,444	7,194	8,503	10,885	7,736
Processing	28,338	18,836	21,787	22,988	23,001	26,373	25,468
Transmission and Storage	180	176	340	499	547	1,242	2,036
Distribution	54	30	17	17	17	16	16
Post-Meter	1	1	2	2	2	2	2
Total	**31,894**	**24,945**	**29,780**	**31,145**	**32,407**	**38,740**	**35,353**

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table 3-72: N_2O Emissions from Natural Gas Systems (Metric Tons CO_2 Eq.)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	399	1,225	113	244	176	116	50
Production	4,318	5,795	8,889	4,306	4,669	5,585	4,293
Processing	NO	3,348	3,732	2,975	3,372	5,689	4,765
Transmission and Storage	257	309	382	462	234	630	1,070
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**4,974**	**10,676**	**13,116**	**7,987**	**8,451**	**12,020**	**10,178**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Table 3-73: N_2O Emissions from Natural Gas Systems (Metric Tons N_2O)

Stage	1990	2005	2016	2017	2018	2019	2020
Exploration	1.3	4.1	0.4	0.8	0.6	0.4	0.2
Production	14.5	19.4	29.8	14.4	15.7	18.7	14.4
Processing	NO	11.2	12.5	10.0	11.3	19.1	16.0
Transmission and Storage	0.9	1.0	1.3	1.6	0.8	2.1	3.6
Distribution	NO	NO	NO	NO	NO	NO	NO
Post-Meter	NO	NO	NO	NO	NO	NO	NO
Total	**16.7**	**35.8**	**44.0**	**26.8**	**28.4**	**40.3**	**34.2**

NO (Not Occurring)

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

See Annex 3.6 for the full time series of emissions data, activity data, and emission factors, and additional information on methods and data sources—for example, the specific years of reporting data from EPA's GHGRP that are used to develop certain factors.

This section provides a general overview of the methodology for natural gas system emission estimates in the Inventory, which involves the calculation of CH_4, CO_2, and N_2O emissions for over 100 emissions sources (i.e., equipment types or processes), and then the summation of emissions for each natural gas segment.

The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For most sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered “potential methane factors” and emission reduction data to calculate net emissions. The estimates are developed with an IPCC Tier 2 approach. Tier 1 approaches are not used.

Emission Factors. Key references for emission factors for CH_4 and CO_2 emissions from the U.S. natural gas industry include a 1996 study published by the Gas Research Institute (GRI) and EPA (GRI/EPA 1996), EPA's GHGRP (EPA 2021a), and others.

The 1996 GRI/EPA study developed over 80 CH_4 emission factors to characterize emissions from the various components within the operating segments of the U.S. natural gas system. The GRI/EPA study was based on a combination of process engineering studies, collection of activity data, and measurements at representative natural gas facilities conducted in the early 1990s. Year-specific natural gas CH_4 compositions are calculated using U.S. Department of Energy’s Energy Information Administration (EIA) annual gross production data for National Energy Modeling System (NEMS) oil and gas supply module regions in conjunction with data from the Gas Technology Institute (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001). These year-specific CH_4 compositions are applied to emission factors, which therefore may vary from year to year due to slight changes in the CH_4 composition of natural gas for each NEMS region.

GHGRP Subpart W data were used to develop CH_4, CO_2, and N_2O emission factors for many sources in the Inventory. In the exploration and production segments, GHGRP data were used to develop emission factors used for all years of the time series for well testing, gas well completions and workovers with and without hydraulic fracturing, pneumatic controllers and chemical injection pumps, condensate tanks, liquids unloading, miscellaneous flaring, gathering and boosting pipelines, and certain sources at gathering and boosting stations. In the processing segment, for recent years of the times series, GHGRP data were used to develop emission factors for leaks, compressors, flares, dehydrators, and blowdowns/venting. In the transmission and storage segment, GHGRP data were used to develop factors for all years of the time series for LNG stations and terminals and transmission pipeline blowdowns, and for pneumatic controllers for recent years of the times series.

Other data sources used for CH_4 emission factors include Zimmerle et al. (2015) for transmission and storage station leaks and compressors, GTI (2009 and 2019) for commercial and industrial meters, Lamb et al. (2015) for recent years for distribution pipelines and meter/regulator stations, Zimmerle et al. (2019) for gathering and boosting stations, Bureau of Ocean Energy Management (BOEM) reports, and Fischer et al. (2019) and IPCC (2019) for post-meter emissions.

For CO_2 emissions from sources in the exploration, production and processing segments that use emission factors not directly calculated from GHGRP data, data from the 1996 GRI/EPA study and a 2001 GTI publication were used to adapt the CH_4 emission factors into related CO_2 emission factors. For sources in the transmission and storage segment that use emission factors not directly calculated from GHGRP data, and for sources in the distribution segment, data from the 1996 GRI/EPA study and a 1993 GTI publication were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. CO_2 emissions from post-meter sources (commercial, industrial and vehicles) were estimated using default emission factors from IPCC (2019). CO_2 emissions from post-meter residential sources are included in fossil fuel combustion data.

Flaring N_2O emissions were estimated for flaring sources using GHGRP data.

See Annex 3.6 for more detailed information on the methodology and data used to calculate CH_4, CO_2, and N_2O emissions from natural gas systems.

Activity Data. Activity data were taken from various published data sets, as detailed in Annex 3.6. Key activity data sources include data sets developed and maintained by EPA's GHGRP (EPA 2020); Enverus (Enverus 2021); BOEM; Federal Energy Regulatory Commission (FERC); EIA; the Natural Gas STAR and Methane Challenge Programs annual data; Oil and Gas Journal; and PHMSA.

For a few sources, recent direct activity data are not available. For these sources, either 2019 data were used as a proxy for 2020 data, or a set of industry activity data drivers was developed and used to calculate activity data over the time series. Drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. More information on activity data and drivers is available in Annex 3.6.

A complete list of references for emission factors and activity data by emission source is provided in Annex 3.6.

Calculating Net Emissions. For most sources, net emissions are calculated directly by applying emission factors to activity data. Emission factors used in net emission approaches reflect technology-specific information, and take into account regulatory and voluntary reductions. However, for production, transmission and storage, and distribution, some sources are calculated using potential emission factors, and CH_4 that is not emitted is deducted from the total CH_4 potential estimates. To take into account use of such technologies and practices that result in lower emissions but are not reflected in "potential" emission factors, data are collected on both regulatory and voluntary reductions. Regulatory actions addressed using this method include EPA National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents. Voluntary reductions included in the Inventory are those reported to Natural Gas STAR and Methane Challenge for certain sources. Natural Gas STAR and Methane Challenge reductions were reassessed for this Inventory, see the Recalculations Discussion for more information.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. GHGRP data available (starting in 2011) and other recent data sources have improved estimates of emissions from natural gas systems. To develop a consistent time series, for sources with new data, EPA reviewed available information on factors that may have resulted in changes over the time series (e.g., regulations, voluntary actions) and requested stakeholder feedback on trends as well. For most sources, EPA developed annual data for 1993 through 2010 by interpolating activity data or emission factors or both between 1992 and 2011 data points. Information on time-series consistency for sources updated in this year's Inventory can be found in the Recalculations Discussion below, with additional detail provided in supporting memos (relevant memos are cited in the Recalculations Discussion). For detailed documentation of methodologies, please see Annex 3.5.

Through EPA's stakeholder process on oil and gas in the Inventory, EPA received stakeholder feedback on updates under consideration for the Inventory. Stakeholder feedback is noted below in Recalculations Discussion and Planned Improvements.

The United States reports data to the UNFCCC using this Inventory report along with Common Reporting Format (CRF) tables. This note is provided for those reviewing the CRF tables: The notation key "IE" is used for CO_2 and CH_4 emissions from venting and flaring in CRF table 1.B.2. Disaggregating flaring and venting estimates across the Inventory would involve the application of assumptions and could result in inconsistent reporting and, potentially, decreased transparency. Data availability varies across segments within oil and gas activities systems, and emission factor data available for activities that include flaring can include emissions from multiple sources (flaring, venting and leaks).

Uncertainty

EPA has conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo Simulation technique) to characterize the uncertainty for natural gas systems. For more information on the approach, please see the memoranda *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Natural Gas and Petroleum Systems Uncertainty Estimates* and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019: Update for Natural Gas and Petroleum Systems CO_2 Uncertainty Estimates.*[78]

EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around CH_4 and CO_2 emissions from natural gas systems for the current Inventory. For the CH_4 uncertainty analysis, EPA focused on the 16 highest-emitting sources for the year 2020, which together emitted 76 percent of methane from natural gas systems in 2020, and extrapolated the estimated uncertainty for the remaining sources. For the CO_2 uncertainty analysis, EPA focused on the 3 highest-emitting sources for the year 2020, which together emitted 80 percent of CO_2 from natural gas systems in 2020, and extrapolated the estimated uncertainty for the remaining sources. To estimate uncertainty for N_2O, EPA applied the uncertainty bounds calculated for CO_2. EPA will seek to refine this estimate in future Inventories. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification. The understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve.

The results presented below provide the 95 percent confidence bound within which actual emissions from this source category are likely to fall for the year 2020, using the IPCC methodology. The results of the Approach 2 uncertainty analysis are summarized in Table 3-74. Natural gas systems CH_4 emissions in 2020 were estimated to be between 135.2 and 194.6 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems CO_2 emissions in 2020 were estimated to be between 29.7 and 42.2 MMT CO_2 Eq. at a 95 percent confidence level. Natural gas systems N_2O emissions in 2020 were estimated to be between 0.009 and 0.012 MMT CO_2 Eq. at a 95 percent

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[78] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

confidence level.

Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series. For example, years where many emission sources are calculated with interpolated data would likely have higher uncertainty than years with predominantly year-specific data. In addition, the emission sources that contribute the most to CH_4 and CO_2 emissions are different over the time series, particularly when comparing recent years to early years in the time series. For example, venting emissions were higher and flaring emissions were lower in early years of the time series, compared to recent years. Technologies also changed over the time series (e.g., liquids unloading with plunger lifts and reduced emissions completions were not used early in the time series and cast iron distribution mains were more prevalent than plastic mains in early years). Transmission and gas processing compressor leak and vent emissions were also higher in the early years of the time series.

Table 3-74: Approach 2 Quantitative Uncertainty Estimates for CH_4 and Non-combustion CO_2 Emissions from Natural Gas Systems (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound[b]	Upper Bound[b]
Natural Gas Systems	CH_4	164.9	135.2	194.6	-18%	+18%
Natural Gas Systems	CO_2	35.4	29.7	42.3	-16%	+19%
Natural Gas Systems	N_2O	+	+	+	-16%	+19%

+ Less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for the year 2020 CH_4 and CO_2 emissions.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in Table 3-68 and Table 3-69.

QA/QC and Verification Discussion

The natural gas systems emission estimates in the Inventory are continually being reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies, GHGRP data, regulations, public webcasts, and the Natural Gas STAR Program to assess whether the assumptions in the Inventory are consistent with current industry practices. The EPA has a multi-step data verification process for GHGRP data, including automatic checks during data-entry, statistical analyses on completed reports, and staff review of the reported data. Based on the results of the verification process, the EPA follows up with facilities to resolve mistakes that may have occurred.[79]

As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review of the current Inventory. EPA held stakeholder webinars in September and November of 2021. EPA released memos detailing updates under consideration and requesting stakeholder feedback.

In recent years, several studies have measured emissions at the source level and at the national or regional level and calculated emission estimates that may differ from the Inventory. There are a variety of potential uses of data from new studies, including replacing a previous estimate or factor, verifying or QA of an existing estimate or factor, and identifying areas for updates. In general, there are two major types of studies related to oil and gas greenhouse gas data: studies that focus on measurement or quantification of emissions from specific activities,

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[79] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

processes and equipment, and studies that use tools such as inverse modeling to estimate the level of overall emissions needed to account for measured atmospheric concentrations of greenhouse gases at various scales. The first type of study can lead to direct improvements to or verification of Inventory estimates. In the past few years, EPA has reviewed and in many cases, incorporated data from these data sources. The second type of study can provide general indications of potential over- and under-estimates. In addition, in recent years information from top-down studies has been directly incorporated to quantify emissions from well blowouts.

A key challenge in using these types of studies to assess Inventory results is having a relevant basis for comparison (e.g., the two data sets should have comparable time frames and geographic coverage, and the independent study should assess data from the Inventory and not another data set, such as the Emissions Database for Global Atmospheric Research, or "EDGAR"). In an effort to improve the ability to compare the national-level Inventory with measurement results that may be at other spatial or temporal scales, a team at Harvard University along with EPA and other coauthors developed a gridded inventory of U.S. anthropogenic methane emissions with 0.1 degree x 0.1 degree spatial resolution, monthly temporal resolution, and detailed scale-dependent error characterization.[80] The gridded methane inventory is designed to be consistent with the U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014* estimates for the year 2012, which presents national totals.[81] An updated version of the gridded inventory is being developed and will improve efforts to compare results of the Inventory with atmospheric studies.

Recalculations Discussion

EPA received information and data related to the emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. In September 2021, EPA released draft memoranda that discussed changes under consideration, and requested stakeholder feedback on those changes. EPA then updated the memoranda to document the methodology implemented in the current Inventory.[82] Memoranda cited in the Recalculations Discussion below are: *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Updates for Anomalous Events Including Well Blowout and Well Release Emissions* (*Anomalous Events* memo), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Updates for Activity Data* (*Activity Data* memo), *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Updates for Gas STAR and Methane Challenge Reductions* (*Reductions* memo), and *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Updates for Post-Meter Emissions* (*Post-Meter* memo).

EPA thoroughly evaluated relevant information available and made several updates to the Inventory, including adding well blowout emissions, using PHMSA data to update underground storage well counts, reassessing the Gas STAR reductions data and incorporating Methane Challenge data, and incorporating post-meter emissions. These changes are discussed in detail below. In addition, certain sources did not undergo methodological updates, but CH_4 and/or CO_2 emissions changed by greater than 0.05 MMT CO_2 Eq., comparing the previous estimate for 2019 to the current (recalculated) estimate for 2019. For sources without methodological updates, the emissions changes were mostly due to GHGRP data submission revisions and updates to well counts in the Enverus dataset.

The combined impact of revisions to 2019 natural gas systems CH_4 emissions, compared to the previous Inventory, is an increase from 167.7 to 178.4 MMT CO_2 Eq. (10.7 MMT CO_2 Eq., or 6 percent). The recalculations resulted in an average increase in the annual CH_4 emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 13.2 MMT CO_2 Eq., or 8.1 percent.

The combined impact of revisions to 2019 natural gas systems CO_2 emissions, compared to the previous Inventory, is an increase from 37.2 MMT to 38.7 MMT, or 4 percent. The recalculations resulted in an average decrease in

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[80] See https://www.epa.gov/ghgemissions/gridded-2012-methane-emissions.

[81] See https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

[82] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2020) Inventory are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 0.1 MMT CO$_2$ Eq., or 0.3 percent.

The combined impact of revisions to 2019 natural gas systems N$_2$O emissions, compared to the previous Inventory, is an increase from 11.3 kt CO$_2$ Eq. to 12.0 kt CO$_2$ Eq., or 6 percent. The recalculations resulted in an average decrease in emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 1 percent.

In Table 3-75 and Table 3-76 below are categories in Natural Gas Systems with recalculations resulting in a change of greater than 0.05 MMT CO$_2$ Eq., comparing the previous estimate for 2019 to the current (recalculated) estimate for 2019. No changes made to N$_2$O estimates resulted in a change greater than 0.05 MMT CO$_2$ Eq. For more information, please see the Recalculations Discussion below.

Table 3-75: Recalculations of CO$_2$ in Natural Gas Systems (MMT CO$_2$)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO$_2$ due to Recalculations	***Previous Estimate Year 2019, 2021 Inventory***	**Current Estimate Year 2019, 2022 Inventory**	**Current Estimate Year 2020, 2022 Inventory**
Exploration	***0.2***	**0.2**	**0.1**
Production	***11.0***	**10.9**	**7.7**
Misc. Onshore Production Flaring	*1.8*	1.9	1.1
Large Tanks with Flares	*0.7*	0.6	0.6
Processing	***24.8***	**26.4**	**25.5**
Flares	*8.3*	9.8	7.9
Transmission and Storage	***1.2***	**1.2**	**2.0**
Distribution	*+*	+	+
Post-Meter	*+*	+	+
Total	***37.2***	**38.7**	**35.4**

+ Does not exceed 0.05 MMT CO$_2$.

Table 3-76: Recalculations of CH$_4$ in Natural Gas Systems (MMT CO$_2$ Eq.)

Segment and Emission Sources with Changes of Greater than 0.05 MMT CO$_2$ due to Recalculations	***Previous Estimate Year 2019, 2021 Inventory***	**Current Estimate Year 2019, 2022 Inventory**	**Current Estimate Year 2020, 2022 Inventory**
Exploration	***0.5***	**1.9**	**0.2**
Well Blowouts	*0.0*	1.3	0.0
Production	***97.1***	**95.0**	**86.4**
Produced Water	*4.7*	4.0	3.5
Pneumatic Controllers	*28.2*	25.6	23.8
Gas Engines	*6.3*	5.8	5.7
Miscellaneous Onshore Flaring	*0.2*	0.2	0.1
Small Tanks w/o Flares	*0.5*	0.5	0.3
G&B Station Sources	*40.9*	39.9	37.5
Gathering Pipeline Leaks	*2.8*	2.9	3.2
Gathering Pipeline Blowdowns	*0.8*	0.2	0.2
Processing	***12.4***	**12.6**	**12.4**
Flares	*0.9*	1.1	0.9
Transmission and Storage	***43.7***	**43.4**	**40.6**
Reciprocating Compressors (Transmission)	*10.2*	10.2	10.5
Wells (Storage)	*0.4*	0.3	0.3
Pipeline Venting	*5.0*	4.7	5.5
Distribution	***14.0***	**13.9**	**13.9**
Post-Meter	***NA***	**11.4**	**11.5**
Total	***167.7***	**178.4**	**164.9**

NA (Not Applicable)

Exploration

Well Blowouts (Methodological Update)

EPA added estimates for well blowout emissions into the Inventory for three discrete well blowout events, using emission estimates calculated in Pandey et al. (2019), Cusworth et al. (2021), and Maasakkers et al. 2022).

Pandey et al. (2019) calculated emissions from a 20-day well blowout in Ohio occurring in February to March 2018 using data collected from Tropospheric Monitoring Instrument (TROPOMI).

Cusworth et al. (2021) calculated emissions from a 20-day well blowout (starting November 1, 2019) in Texas using data collected from a combination of satellite instruments including TROPOMI, GHGSat-D, the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument, and the PRecursore IperSpettrale della Missione Applicativa (PRISMA) satellite imaging spectrometer.

Maasakkers et al. (2022) calculated emissions from a 38-day well blowout (starting August 30, 2019) in Louisiana using data collected from TROPOMI and VIIRS.

The *Anomalous Events* memo contains additional information on this update.

Table 3-77: Well Blowout National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Gas Well Blowout	NO	NO	NO	NO	60,000	53,800	NO
Previous Estimate	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Production

Produced Water (Recalculation with Updated Data)

Produced water CH_4 emissions increased by an average of 16 percent across the 1990 to 2019 time series and decreased by 14 percent in 2019, compared to the previous Inventory. These changes were due to updates to the handling of Enverus data and NEI's O&G Tool data for six states (IL, IN, KS, PA, OK, and WV). The largest changes occurred earlier in the time series (e.g., 1990 to 1999), where the estimate of the annual volume of produced water increased by an average of 41 percent over the previous estimate. This change was primarily due to revised data available from the NEI for OK. The revised NEI data were obtained for 2002, 2005, 2008, 2011, 2014, and 2016-2020 (EPA 2021f). For the missing years in the time-series, EPA estimated state-level produced water volumes (for IL, IN, KS, PA, OK, and WV) using the average ratio of produced water to gas production calculated for 2002, 2005, 2008, 2011, and 2014. Revised produced water data for the remaining states is from Enverus (Enverus 2021).

Table 3-78: Produced Water National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Gas Well Produced Water	121,867	153,709	142,777	145,965	150,073	160,548	131,322
Previous Estimate	*82,250*	*139,453*	*154,394*	*157,488*	*188,601*	*187,070*	*NA*

NA (Not Applicable)

Pneumatic Controllers (Recalculation with Updated Data)

Pneumatic controller CH_4 emission estimates decreased by an average of 1.5 percent across the 1990 to 2019 time series and decreased by 9 percent in 2019, compared to the previous Inventory. These changes were due to GHGRP submission revisions.

Table 3-79: Production Segment Pneumatic Controller National Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Low Bleed	0	23,565	32,794	36,102	35,069	33,089	32,224
High Bleed	308,908	471,540	107,928	113,112	92,941	72,923	43,096
Intermittent Bleed	201,446	546,397	928,445	955,682	944,864	918,666	875,399
Total Emissions	**510,354**	**1,041,503**	**1,069,168**	**1,104,896**	**1,072,874**	**1,024,678**	**950,718**
Previous Estimate	*482,334*	*1,062,685*	*1,063,791*	*1,103,082*	*1,075,645*	*1,126,531*	*NA*

NA (Not Applicable)

Gas Engines (Recalculation with Updated Data)

Gas engine (combustion slip) CH_4 emissions increased by an average of 37 percent across the 1990 to 2019 time series and increased by 81 percent in 2019, compared to the previous Inventory. These changes were due to updates to well counts in the Enverus dataset.

Table 3-80: Gas Engine National Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Gas Engines	115,689	198,004	214,661	197,218	207,051	202,052	197,074
Previous Estimate	*116,684*	*129,715*	*124,835*	*120,272*	*116,437*	*111,886*	*NA*

NA (Not Applicable)

Miscellaneous Production Flaring (Recalculation with Updated Data)

Miscellaneous production flaring CH_4 emissions increased by an average of 6 percent across the 1990 to 2019 time series and increased by 8 percent in 2019, compared to the previous Inventory. CO_2 emissions for this source increased across the 1990 to 2019 time series by an average of 1 percent and increased by 5 percent in 2019. These changes were due to GHGRP submission revisions.

Table 3-81: Miscellaneous Production Flaring National Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Miscellaneous Flaring-Gulf Coast Basin	NO	547	649	524	401	1,268	939
Miscellaneous Flaring-Williston Basin	NO	+	+	107	65	9	30
Miscellaneous Flaring-Permian Basin	NO	1,354	2,315	3,539	2,911	5,096	2,946
Miscellaneous Flaring-Other Basins	NO	557	1,937	1,414	1,587	1,791	980
Total Emissions	**NO**	**2,458**	**4,902**	**5,584**	**4,964**	**8,164**	**4,894**
Previous Estimate	*NO*	*2,269*	*4,849*	*5,552*	*5,029*	*7,680*	*NA*

+ Does not exceed 0.5 metric tons.
NO (Not Occurring)
NA (Not Applicable)

Table 3-82: Miscellaneous Production Flaring National Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Miscellaneous Flaring-Gulf Coast Basin	NO	166	234	209	137	399	251
Miscellaneous Flaring-Williston Basin	NO	+	+	10	6	4	4
Miscellaneous Flaring-Permian Basin	NO	260	500	622	707	1,159	591
Miscellaneous Flaring-Other Basins	NO	117	427	304	493	342	213
Total Emissions	**NO**	**543**	**1,161**	**1,145**	**1,344**	**1,904**	**1,060**
Previous Estimate	*NO*	*543*	*1,162*	*1,152*	*1,388*	*1,820*	*NA*

+ Does not exceed 0.5 kt.

NO (Not Occurring)

NA (Not Applicable)

Production Storage Tanks (Recalculation with Updated Data)

Methane emissions for small production storage tanks without flares decreased by an average of 0.5 percent across the 1990 to 2019 time series and decreased by 15 percent in 2019, compared to the previous Inventory. The large production storage tank with flares CO_2 emissions estimate decreased by an average of 1 percent across the time series and by 21 percent in 2019, compared to the previous Inventory. These changes were due to GHGRP submission revisions.

Table 3-83: Production Storage Tanks National Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Small Tanks w/o Flares	10,144	7,760	22,584	16,123	16,753	18,591	13,613
Previous Estimate	*10,180*	*7,763*	*22,520*	*16,013*	*16,668*	*21,951*	*NA*

NA (Not Applicable)

Table 3-84: Production Storage Tanks National Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Large Tanks w/ Flares	**292**	**367**	**1,107**	**1,085**	**779**	**573**	**552**
Previous Estimate	*293*	*369*	*1,114*	*1,090*	*781*	*723*	*NA*

NA (Not Applicable)

Gathering and Boosting (G&B) Stations (Recalculation with Updated Data)

Methane emission estimates for sources at gathering and boosting stations decreased in the current Inventory by less than 0.1 percent across the time series and decreased by 1 percent in 2019, compared to the previous Inventory. The G&B sources with the largest decrease in CH_4 emissions estimates for year 2019, compared to the previous Inventory, are compressors (decrease of 3.5 kt, or 1 percent), gas engines (decrease of 4.8 kt, or 1 percent), and station blowdowns (decrease of 25 kt or 36 percent). Intermittent bleed pneumatic device CH_4 emissions increased by 11 kt, or 6 percent in 2019, compared to the previous Inventory. These changes were due to GHGRP submission revisions.

Table 3-85: Gathering Stations Sources National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Compressors	130,165	165,664	261,677	280,355	298,220	305,896	306,935
Station Blowdowns	20,517	26,113	41,247	63,852	78,548	43,865	44,881

Intermittent Bleed Pneumatic Devices	79,716	101,456	160,351	191,528	173,811	181,860	172,429
Gas Engines	172,279	219,263	346,340	371,406	395,047	405,617	407,130
Other Gathering Sources	245,501	312,455	493,474	470,489	466,178	532,944	432,570
Total Emissions	**648,179**	**824,951**	**1,303,088**	**1,377,631**	**1,411,804**	**1,470,183**	**1,363,946**
Previous Estimate	*652,538*	*823,648*	*1,299,276*	*1,359,628*	*1,398,994*	1,491,704	*NA*

NA (Not Applicable)

Gathering Pipeline Leaks

Gathering pipeline leak CH_4 emissions estimates increased by an average of 0.2 percent across the 1990 to 2019 time series and increased by 3 percent in 2019, compared to the previous inventory. The emission changes were due to GHGRP submission revisions.

Table 3-86: Gathering Pipeline Leak National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Pipeline Leaks	81,659	120,311	139,170	135,940	119,890	116,470	126,661
Previous Estimate	*78,046*	*120,280*	*138,645*	*141,873*	*116,590*	*112,881*	*NA*

NA (Not Applicable)

Gathering Pipeline Blowdowns

Gathering pipeline blowdowns CH_4 emissions estimates decreased by an average of 0.1 percent across the 1990 to 2019 time series and decreased by 73 percent in 2019, compared to the previous inventory. The emission changes were due to GHGRP submission revisions.

Table 3-87: Gathering Pipeline Blowdowns National CH_4 Emissions (Metric Tons CH_4)

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Pipeline Blowdowns	8,841	13,026	15,068	19,777	16,060	8,377	9,390
Previous Estimate	*8,482*	*13,072*	*15,068*	*19,777*	*16,060*	*31,477*	*NA*

NA (Not Applicable)

Well Counts (Recalculation with Updated Data)

EPA uses annual producing gas well counts as an input for estimates of emissions from multiple sources in the Inventory, including exploration well testing, pneumatic controllers, chemical injection pumps, well workovers, and equipment leaks. Annual well count data are obtained from Enverus for the entire time series during each Inventory cycle. In addition, well counts for Illinois and Indiana were more fully incorporated for this Inventory, based on information available from state agencies or from EIA. There are an average of 400 gas wells for Illinois and 1,500 gas wells for Indiana, across the time series. Annual gas well counts increased by an average of 1 percent across the 1990 to 2019 time series and by 1 percent in 2019, compared to the previous Inventory.

Table 3-88: National Gas Well Counts

Source	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Gas Wells	193,344	351,129	432,952	429,952	426,372	420,439	410,246
Previous Estimate	*185,141*	*351,982*	*429,697*	*427,046*	*424,507*	*417,507*	*NA*

NA (Not Applicable)

In January 2022, EIA released an updated time series of national oil and gas well counts (covering 2000 through 2020). EIA estimates 936,984 total wells for year 2020. EPA's total well count for 2020 is 939,665. EPA well counts are higher due to the inclusion of wells for Illinois and Indiana in the current Inventory. EIA does not include wells for these two states. If these states are excluded from the well count comparison (i.e., well counts are compared only for the states that are in both EIA and EPA datasets), EPA's well counts are about 2 percent lower than EIA's in

2020, in part due to well definitions. EIA's well counts include side tracks (i.e., secondary wellbore away from original wellbore in order to bypass unusable formation, explore nearby formations, or other reasons), completions, and recompletions, and therefore are expected to be higher than EPA's which include only producing wells. Note, EPA and EIA use a different threshold for distinguishing between oil versus gas wells (EIA uses 6 mcf/bbl, while EPA uses 100 mcf/bbl), which results in EIA having a lower fraction of oil wells (e.g., 44 percent versus EPA's 56 percent in 2020) and a higher fraction of gas wells (e.g., 56 percent versus EPA's 44 percent in 2020) than EPA.

Processing

Flares (Recalculation with Updated Data)

Processing segment flare CO_2 emission estimates increased by an average of less than 1 percent across the 1993 to 2019 time series and increased by 19 percent for 2019, compared to the previous Inventory. Processing segment flare CH_4 emission estimates increased by nearly 3 percent across the 2011 to 2019 time series and by 24 percent for 2019, compared to the previous Inventory. These changes were due to GHGRP submission revisions.

Table 3-89: Processing Segment Flares National CO_2 Emissions (kt CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Flares	NO	3,517	5,123	5,590	6,176	9,837	7,879
Previous Estimate	*NO*	*3,517*	*5,246*	*5,726*	*6,394*	*8,257*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Table 3-90: Processing Segment Flares National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Flares	NO	NA	20,199	24,533	24,195	43,518	35,704
Previous Estimate	*NO*	*NA*	*20,239*	*24,498*	*24,373*	*35,147*	*NA*

NA (Not Applicable)
NO (Not Occurring)

Transmission and Storage

Underground Storage Well Leaks (Methodological Update)

EPA updated the methodology for underground storage well leaks to use storage well count data from PHMSA (PHMSA 2021b). The PHMSA storage well data were identified by stakeholders during the stakeholder process for the previous Inventory. The *Activity Data* memo presents considerations for this update. PHMSA storage well counts are used for 2017 forward, storage well counts for 1990 to 1992 are retained from the previous Inventory methodology, and linear interpolation is applied from the 1992 to 2017 values to estimate intermediate years.

Underground storage well leak CH_4 emission estimates decreased by an average of 11 percent for the 1990 to 2019 time series and by 27 percent in 2019, compared to the previous Inventory.

Table 3-91: Underground Storage Well Leak National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Storage Well Leaks	13,565	12,295	32,891	11,483	11,434	11,326	11,255
Previous Estimate	*13,565*	*14,910*	*34,716*	*13,632*	*15,439*	*15,495*	*NA*

NA (Not Applicable)

Transmission Station Reciprocating Compressors (Recalculation with Updated Data)

Methane emission estimates from reciprocating compressors at transmission compressor stations increased by an average of 0.2 percent for 2011 to 2019, compared to the previous Inventory. This increase in the CH_4 emission estimates was due to GHGRP submission revisions.

Table 3-92: Transmission Station Reciprocating Compressors National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Transmission Station – Reciprocating Compressors	NA	NA	347,178	349,784	375,187	409,709	419,480
Previous Estimate	*NA*	*NA*	*345,224*	*347,830*	*373,233*	*406,453*	*NA*

NA (Not Applicable)

Transmission Pipeline Venting (Recalculation with Updated Data)

Pipeline venting CH_4 emissions estimates increased by an average of 0.5 percent across the 2011 to 2019 time series and decreased by 6 percent in 2019, compared to the previous Inventory. The emission changes were due to GHGRP submission revisions.

Table 3-93: Transmission Pipeline Venting National CH_4 Emissions (Metric Tons CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Pipeline Venting	177,951	183,159	249,933	200,542	208,438	187,268	221,278
Previous Estimate	*177,951*	*183,159*	*250,153*	*185,003*	*185,050*	*199,370*	*NA*

NA (Not Applicable)

Distribution

There were no methodological updates to the distribution segment, and recalculations due to updated data resulted in average decreases in calculated CH_4 and CO_2 emissions over the time series of less than 1 percent.

Natural Gas STAR and Methane Challenge Reductions

EPA has reassessed the voluntary emission reductions reported under the Natural Gas STAR and Methane Challenge programs for this Inventory. The latest reported data were paired with sources in the Inventory that use potential emissions approaches and incorporated into the estimates (e.g., gas engines). In recent years, the Inventory used 2013 Gas STAR reductions data for all years from 2013 forward. The *Reductions* memo provides the full considerations for this update. As in previous Inventories, reductions data are only included in the Inventory if the emission source uses “potential” emission factors, and for Natural Gas STAR reductions, short-term emission reductions are assigned to the reported year only, while long-term emission reductions are assigned to the reported year and every subsequent year in the time series. Voluntary emission reductions decreased by an average of 55 percent across the 1990 to 2019 time series, compared to the previous Inventory.

In reviewing calculated net emissions on a source-by-source basis, it was determined that the updated incorporation of voluntary program reductions data resulted in calculated negative emissions (i.e., the absolute value of the reductions is greater than the potential emissions from that source) for certain sources in some years.

The sources with calculated negative net emissions (and years of negative emissions) include:

- Production segment
    - Compressor blowdowns (2001-2020)
    - Compressor starts (1994-2020)
    - Dehydrator vents (2010-2011)
- Transmission segment
    - Dehydrator vents (1997-2020)
    - Pipeline leaks (1998-1999, 2007-2012, 2014, 2017-2018)

- Distribution segment
    - Pipeline blowdowns (1997, 2005-2006)
    - PRV releases (2002)

EPA removed Gas STAR reductions entirely for sources with more than ten years of negative calculated emissions (production segment compressor blowdowns and compressor starts, and transmission segment dehydrator vents and pipeline leaks). For the remaining sources with negative emissions (production segment dehydrator vents and distribution segment pipeline blowdowns and PRV releases), calculated negative emissions occur for a maximum of three years in the time series. EPA replaced the negative net emissions value with zero for the years of negative net emissions for these sources.

In addition, as in previous Inventories, EPA has removed the reductions for years 1990 to 1992 as those are already considered to be included in current emission factors.

Table 3-94: Natural Gas STAR and Methane Challenge Emission Reductions (Metric Tons CH_4 Reduction)

Source	1990		2005		2016	2017	2018	2019	2020
Production	NA		71,220		88,780	100,364	82,782	84,380	84,380
Transmission and Storage	NA		72,856		115,408	123,082	143,493	153,828	153,828
Distribution	NA		6,605		4,209	4,547	4,987	3,825	3,825
Total	**NA**		**150,681**		**208,397**	**227,993**	**231,262**	**242,033**	**242,033**
Previous Estimate	*NA*		*420,902*		*519,798*	*519,798*	*519,798*	*519,798*	*NA*

NA (Not Applicable)

Post-Meter

The Inventory was updated to include an estimate for post-meter emissions. Post-meter emission factors are presented in the *2019 Refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* under natural gas systems (IPCC 2019). Post-meter emission sources include certain leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles. The specific sources within the post-meter estimate are as follows:

- Appliances in residential and commercial sectors—Leakage from house piping and natural gas appliances such as furnaces, water heaters, stoves and ovens, and barbecues/grills.
- Leakage at industrial plants and power stations (EGUs) —Leakage from internal piping.
- Natural gas fueled vehicles—Emissions from vehicles with alternative fuels produced from natural gas e.g., LNG, CNG, propane. Emissions for natural gas-fueled vehicles include releases from dead volumes during fueling, emptying of gas cylinders of high-pressure interim storage units, for execution of pressure tests and relaxation of residual pressure from vehicles' gas tanks, or decommissioning.

EPA’s considerations for this source are documented in the *Post-Meter* memo. For each of the emission sources, emissions are estimated by multiplying emission factors (e.g., emission rate per unit fuel consumption or per natural gas household) by corresponding activity data (e.g., fuel consumption, or number of natural gas households). The methodology and data sources used for each are discussed here.

For residential sources, EPA applied the CH_4 emission factor from Fischer et al. (2018), which is on an emission rate per natural gas household basis. The Fischer et al. EF accounts for passive house leak emissions and appliance leak emissions. Activity data used to estimate CH_4 emissions from residential post-meter sources are national counts of natural gas households (i.e., households using natural gas for space heating, water heating, cooking, and other purposes). EPA used national-level data on natural gas households from the U.S. Census Bureau’s *American Housing Survey* publications (AHS 2021). AHS data are published on a biennial basis and EPA estimated data for missing time-series years using the average of data from the years immediately before and after the missing year.

The residential post-meter emission factor captures combustion emissions for gas appliances along with unburned methane emissions. To ensure there is no double-counting with residential natural gas combustion emissions (i.e., from stationary fuel combustion), EPA subtracted the CH_4 emissions for the residential natural gas combustion source (see Section 3.1 CH4 and N2O from Stationary Combustion) from the estimated residential post-meter emissions.

For commercial post-meter emissions, EPA used the IPCC default CH_4 and CO_2 emission factors (IPCC 2019) and national data on commercial buildings, by fuel types and end use, from EIA's *Commercial Buildings Energy Consumption Survey* (CBECS 2021). CBECS contains data on the number of commercial buildings that use natural gas for specific end uses such as space heating, water heating, and cooking but does not indicate the number of appliances at commercial buildings. The CBECS data are only available for 1992, 1995, 1999, 2003, 2012, and 2018. EPA estimated national commercial appliance counts for these years by assuming one appliance of each type per commercial building using natural gas for that appliance type. Using the estimated appliance counts and natural gas commercial meter counts, EPA developed an average estimate of 1 appliance per commercial meter. EPA then estimated annual commercial appliance counts for the time-series by applying the estimate of 1 appliance per commercial meter to time-series data on natural gas commercial meter counts.

For industrial post-meter emissions, EPA used the IPCC default CH_4 and CO_2 emission factors (IPCC 2019) and activity data on natural gas consumption in the industrial and EGU sectors from EIA (EIA 2021b).

For vehicle post-meter emissions, EPA used the IPCC default CH_4 and CO_2 emission factors (IPCC 2019) and estimated the national natural gas fueled vehicle population based on data from EPA's Motor Vehicle Emission Simulator model (MOVES) (EPA 2020).

In 2020, total CH_4 emissions from all post-meter sources were estimated to be 459.1 kilotons (11.5 MMT CO_2 Eq.). This represents a 35 percent increase from 1990 levels and a slight increase of 1 percent from the previous year. Approximately 53 percent of all post-meter CH_4 emissions are from the industrial and EGUs sub-segment, 42 percent from the residential sub-segment, and approximately 5 percent from the commercial sub-segment. Natural gas vehicles contribute less than 0.05 percent of total post-meter CH_4 emissions. CO_2 emissions from post-meter are 2.2 kt, contributing less than 0.01 percent of total CO_2 from natural gas systems Inventory. CO_2 emissions from residential appliances are assumed to be captured by residential natural gas combustion source and are not included under post-meter estimates.

Table 3-95: Post-Meter Segment National CH_4 Emissions (Metric Tons CH_4)

Activity	1990	2005	2016	2017	2018	2019	2020
Residential	142,755	169,828	186,242	189,537	188,637	190,478	192,199
Commercial	16,945	20,792	21,899	22,000	22,073	22,206	22,508
Industrial and EGUs	130,251	153,837	218,144	212,931	234,483	243,838	244,333
Natural Gas Vehicles	+	7	21	24	27	30	32
Total	**289,951**	**344,464**	**426,306**	**424,492**	**445,220**	**456,551**	**459,072**
Previous Estimate	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*

+ Does not exceed 0.5 metric tons.

Note: Totals may not sum due to independent rounding.

Table 3-96: Post-Meter Segment National CO_2 Emissions (kt CO_2)

Activity	1990	2005	2016	2017	2018	2019	2020
Residential	IE	IE	IE	IE	IE	IE	IE
Commercial	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Industrial and EGUs	1.1	1.3	1.8	1.8	1.9	2.0	2.0
Natural Gas Vehicles	+	+	+	+	+	+	+
Total	**1.2**	**1.4**	**2.0**	**1.9**	**2.1**	**2.2**	**2.2**
Previous Estimate	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*	*NE*

+ Does not exceed 0.05 kt.

IE (Included Elsewhere). Due to calculation methodologies, residential post-meter CO_2 fugitive emissions are included in the fossil fuel combustion values.

NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

Planned Improvements

Post-Meter Fugitive Emissions

EPA received feedback on this update through the September 2021 *Post-Meter Memo* and the public review of the current Inventory. EPA received comments suggesting that EPA delay the inclusion of post-meter estimates. Stakeholders presented concerns on the use of Fischer et al. study data in developing national estimates for residential post-meter sources. Stakeholders suggested that the Fischer et al. study, conducted in California, is not representative of national activity. EPA reviewed other residential post-meter studies, including the Merrin and Francisco (2019) study conducted in Boston and Indianapolis (refer to *Post-Meter* memo for more details). The other studies reviewed covered only emissions from major appliances, whereas the Fischer et al. study covered emissions from passive house leaks and gas appliances (both major and minor appliances). A stakeholder comment also suggested that a phase out of pilot lights occurring over the past several decades should be reflected in the time series.

EPA will continue to track studies that may include data that could be used to update the emission factor for residential post-meter emissions, and also to use instead of IPCC default values for commercial, industrial, and vehicle post-meter emissions. EPA may consider approaches to take into account changes in emissions rates over the time series such as applying default IPCC factors for residential emissions for earlier years of the time series.

Transmission Station Counts

Stakeholder feedback suggested alternate approaches for calculating the annual number of transmission stations. EPA will consider the update for the next (1990 through 2021) Inventory. Stakeholder feedback on the public review draft recommended against use of proprietary data sources for this activity data set. EPA will consider using the proprietary data sets for QA/QC of EPA’s activity data estimates.

Upcoming Data, and Additional Data that Could Inform the Inventory

EPA will assess new data received by the EPA Methane Challenge Program on an ongoing basis, which may be used to validate or improve existing estimates and assumptions.

EPA continues to track studies that contain data that may be used to update the Inventory. EPA will also continue to assess studies that include and compare both top-down and bottom-up emission estimates, which could lead to improved understanding of unassigned high emitters (e.g., identification of emission sources and information on frequency of high emitters) as recommended in stakeholder comments.

EPA also continues to seek new data that could be used to assess or update the estimates in the Inventory. For example, stakeholder comments have highlighted areas where additional data that could inform the Inventory are currently limited or unavailable:

- Tank measurements and tank and flaring malfunction and control efficiency data.
- Improved equipment leak data (activity and emissions data).
- Activity data and emissions data for production facilities that do not report to GHGRP.
- Onshore mud degassing.
- Anomalous leak events information throughout the time series and for future years.

Emission sources for which calculated emissions are negative when Gas STAR or Methane Challenge reductions are applied. See Recalculations Discussion section on Natural Gas STAR and Methane Challenge for the list of sources.

EPA received stakeholder feedback through comments on the public review draft of the current Inventory. Several stakeholders asserted that methane emissions are undercounted in natural gas systems. A stakeholder commented suggested developing the inventory using a strategy that combines information from satellites, aircraft-based instruments, and ground-based sensors. Stakeholder feedback on the public review draft recommended use of updated emission factors for pneumatic controllers. A stakeholder suggested that current emission factors underestimate emissions from combustion slip.

EPA will continue to seek available data on these and other sources as part of the process to update the Inventory.

3.8 Abandoned Oil and Gas Wells (CRF Source Categories 1B2a and 1B2b)

The term "abandoned wells", as used in the Inventory, encompasses various types of oil and gas wells, including orphaned wells and other non-producing wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, and idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, and abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

The U.S. population of abandoned oil and gas wells (including orphaned wells and other non-producing wells) is around 3.7 million (with around 3.0 million abandoned oil wells and 0.7 million abandoned gas wells). The methods to calculate emissions from abandoned wells involve calculating the total populations of plugged and unplugged abandoned oil and gas wells in the U.S. and the application of emission factors. An estimate of the number of orphaned wells within this population is not developed as part of the methodology. Other groups have developed estimates of the total number of orphaned wells. The Interstate Oil and Gas Compact Commission for example estimates 92,198 orphaned wells in the U.S. (IOGCC 2021). State applications for grants to plug orphaned wells indicate over 130,000 orphaned wells in the U.S. (Department of Interior 2022). Wells that are plugged have much lower average emissions than wells that are unplugged (less than 1 kg CH_4 per well per year, versus over 100 kg CH_4 per well per year). Around 41 percent of the abandoned well population in the United States are plugged. This fraction has increased over the time series (from around 23 percent in 1990) as more wells fall under regulations and programs requiring or promoting plugging of abandoned wells.

Abandoned oil wells. Abandoned oil wells emitted 219 kt CH_4 and 4 kt CO_2 in 2020. Emissions of both gases increased by 2 percent from 1990, while the total population of abandoned oil wells increased 38 percent.

Abandoned gas wells. Abandoned gas wells emitted 57 kt CH_4 and 3 kt CO_2 in 2020. Emissions of both gases increased by 25 percent from 1990, while the total population of abandoned gas wells increased 74 percent.

Table 3-97: CH_4 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Abandoned Oil Wells	5.4	5.5	5.5	5.5	5.5	5.5	5.5
Abandoned Gas Wells	1.1	1.3	1.4	1.4	1.4	1.5	1.4
Total	**6.5**	**6.8**	**6.9**	**6.9**	**6.9**	**7.0**	**6.9**

Note: Totals may not sum due to independent rounding.

Table 3-98: CH_4 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Abandoned Oil Wells	215	222	218	219	220	221	219

Abandoned Gas Wells	46	51	57	57	57	58	57
Total	**261**	**273**	**275**	**276**	**277**	**279**	**276**

Note: Totals may not sum due to independent rounding.

Table 3-99: CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2)

Activity	1990	2005	2016	2017	2018	2019	2020
Abandoned Oil Wells	+	+	+	+	+	+	+
Abandoned Gas Wells	+	+	+	+	+	+	+
Total	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.05 MMT CO_2.

Table 3-100: CO_2 Emissions from Abandoned Oil and Gas Wells (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Abandoned Oil Wells	4	5	4	4	4	4	4
Abandoned Gas Wells	2	2	2	3	3	3	3
Total	**6**	**7**	**7**	**7**	**7**	**7**	**7**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

EPA uses a Tier 2 method from IPCC 2019 to quantify emissions from abandoned oil and gas wells, based on the number of plugged and unplugged abandoned wells in the Appalachian region and in the rest of the U.S., and emission factors for plugged and unplugged abandoned wells in Appalachia and the rest of the U.S. Methods for abandoned wells are unavailable in IPCC 2006. The details of this approach and of the data sources used are described in the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo).*

EPA developed abandoned well CH_4 emission factors using data from Kang et al. (2016) and Townsend-Small et al. (2016). Plugged and unplugged abandoned well CH_4 emission factors were developed at the national-level (using emission data from Townsend-Small et al.) and for the Appalachia region (using emission data from measurements in Pennsylvania and Ohio conducted by Kang et al. and Townsend-Small et al., respectively). The Appalachia region emissions factors were applied to abandoned wells in states in the Appalachian basin region, and the national-level emission factors were applied to all other abandoned wells. EPA developed abandoned well CO_2 emission factors using the CH_4 emission factors and an assumed ratio of CO_2-to-CH_4 gas content, similar to the approach used to calculate CO_2 emissions for many sources in Petroleum Systems and Natural Gas Systems. For abandoned oil wells, EPA used the Petroleum Systems default production segment associated gas ratio of 0.020 MT CO_2/MT CH_4, which was derived through API TankCalc modeling runs. For abandoned gas wells, EPA used the Natural Gas Systems default production segment CH_4 and CO_2 gas content values (GRI/EPA 1996, GTI 2001) to develop a ratio of 0.044 MT CO_2/MT CH_4. The same respective emission factors are applied for each year of the time series.

EPA developed annual counts of abandoned wells for 1990 through 2020 by summing together an annual estimate of abandoned wells in the Enverus data set (Enverus 2021), and an estimate of total abandoned wells not included in the Enverus dataset (see *2018 Abandoned Wells Memo* for additional information on how the value was calculated). References reviewed to develop the number of abandoned wells not included in the Enverus dataset include historical records collected by state agencies and by USGS. To calculate the number of wells not included in the Enverus dataset, estimated abandoned well counts (oil, gas, and dry) for 1975 from historical data available at the state-level (by subtracting total active wells from total drilled wells) and deducted abandoned well counts developed using Enverus data for 1975 for the corresponding states. The resulting total number of abandoned wells (i.e., not included in Enverus data) is then added to the annual abandoned well counts developed using Enverus data for 1990 to 2020.

The total abandoned well population was then split into plugged and unplugged wells by assuming that all abandoned wells were unplugged in 1950 and using year-specific Enverus data to calculate the fraction of plugged abandoned wells (41 percent) in 2020 in that data set. Abandoned wells not included in the Enverus dataset were assumed to be unplugged. Linear interpolation was applied between the 1950 value and 2020 value to calculate the plugged fraction for intermediate years. See the memorandum *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Wells in Natural Gas and Petroleum Systems (2018 Abandoned Wells Memo)* for details.[83] The abandoned wells activity data methodology was also updated for this Inventory; see the Recalculations Discussion section for more information.

Abandoned Oil Wells

Table 3-101: Abandoned Oil Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Plugged abandoned oil wells (number of wells)	507,322	834,303	1,108,361	1,140,315	1,171,441	1,205,046	1,222,510
Unplugged abandoned oil wells (number of wells)	1,660,257	1,758,160	1,761,684	1,768,403	1,772,730	1,779,690	1,762,226
Total Abandoned Oil Wells	**2,167,579**	**2,592,463**	**2,870,046**	**2,908,718**	**2,944,171**	**2,984,736**	**2,984,736**
Abandoned oil wells in Appalachia (percent)	23%	21%	20%	20%	20%	20%	20%
Abandoned oil wells outside of Appalachia (percent)	77%	79%	80%	80%	80%	80%	80%
CH_4 from plugged abandoned oil wells (kt)	0.37	0.56	0.70	0.73	0.74	0.77	0.78
CH_4 from unplugged abandoned oil wells (kt)	214.6	221.3	217.7	218.6	219.1	219.9	217.8
Total CH_4 from Abandoned Oil Wells (kt)	**215.0**	**221.8**	**218.4**	**219.3**	**219.8**	**220.7**	**218.6**
Total CO_2 from Abandoned Oil Wells (kt)	**4.4**	**4.5**	**4.4**	**4.4**	**4.5**	**4.5**	**4.4**

Abandoned Gas Wells

Table 3-102: Abandoned Gas Wells Activity Data, CH_4 and CO_2 Emissions (kt)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Plugged abandoned gas wells (number of wells)	100,295	180,578	273,018	282,358	291,443	301,449	305,818
Unplugged abandoned gas wells (number of wells)	328,226	380,540	433,948	437,880	441,037	445,200	440,831
Total Abandoned Gas Wells	**428,521**	**561,119**	**706,966**	**720,238**	**732,480**	**746,649**	**746,649**
Abandoned gas wells in Appalachia (percent)	29%	25%	23%	23%	23%	23%	23%
Abandoned gas wells outside of Appalachia (percent)	71%	75%	77%	77%	77%	77%	77%
CH_4 from plugged abandoned gas wells (kt)	0.09	0.15	0.20	0.21	0.22	0.22	0.23
CH_4 from unplugged abandoned gas wells (kt)	45.7	50.9	56.3	56.9	57.3	57.8	57.2
Total CH_4 from Abandoned Gas Wells (kt)	**45.8**	**51.0**	**56.6**	**57.1**	**57.5**	**58.0**	**57.5**

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[83] See https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Total CO_2 from Abandoned Gas Wells (kt)	**2.0**		**2.2**		**2.5**	**2.5**	**2.5**	**2.5**	**2.5**

Uncertainty

To characterize uncertainty surrounding estimates of abandoned well emissions, EPA conducted a quantitative uncertainty analysis using the IPCC Approach 2 methodology (Monte Carlo simulation technique). See the *2018 Abandoned Wells Memo* for details of the uncertainty analysis methods. EPA used Microsoft Excel's @RISK add-in tool to estimate the 95 percent confidence bound around total methane emissions from abandoned oil and gas wells in year 2020, then applied the calculated bounds to both CH_4 and CO_2 emissions estimates for each population. The @RISK add-in provides for the specification of probability density functions (PDFs) for key variables within a computational structure that mirrors the calculation of the inventory estimate. EPA used measurement data from the Kang et al. (2016) and Townsend-Small et al. (2016) studies to characterize the CH_4 emission factor PDFs. For activity data inputs (e.g., total count of abandoned wells, split between plugged and unplugged), EPA assigned default uncertainty bounds of ± 10 percent based on expert judgment.

The IPCC guidance notes that in using this method, "some uncertainties that are not addressed by statistical means may exist, including those arising from omissions or double counting, or other conceptual errors, or from incomplete understanding of the processes that may lead to inaccuracies in estimates developed from models." As a result, the understanding of the uncertainty of emission estimates for this category evolves and improves as the underlying methodologies and datasets improve. The uncertainty bounds reported below only reflect those uncertainties that EPA has been able to quantify and do not incorporate considerations such as modeling uncertainty, data representativeness, measurement errors, misreporting or misclassification.

The results presented below in Table 3-103 provide the 95 percent confidence bound within which actual emissions from abandoned oil and gas wells are likely to fall for the year 2020, using the recommended IPCC methodology. Abandoned oil well CH_4 emissions in 2020 were estimated to be between 0.9 and 16.2 MMT CO_2 Eq., while abandoned gas well CH_4 emissions were estimated to be between 0.2 and 4.3 MMT CO_2 Eq. at a 95 percent confidence level. Uncertainty bounds for other years of the time series have not been calculated, but uncertainty is expected to vary over the time series.

Table 3-103: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Abandoned Oil and Gas Wells (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)[b]	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Abandoned Oil Wells	CH_4	5.5	0.9	16.2	-83%	+197%
Abandoned Gas Wells	CH_4	1.4	0.2	4.3	-83%	+197%
Abandoned Oil Wells	CO_2	0.004	0.001	0.013	-83%	+197%
Abandoned Gas Wells	CO_2	0.003	0.0004	0.007	-83%	+197%

[a] Range of emission estimates estimated by applying the 95 percent confidence intervals obtained from the Monte Carlo Simulation analysis conducted for total abandoned oil and gas well CH_4 emissions in year 2020.

[b] All reported values are rounded after calculation. As a result, lower and upper bounds may not be duplicable from other rounded values as shown in table.

QA/QC and Verification Discussion

The emission estimates in the Inventory are continually reviewed and assessed to determine whether emission factors and activity factors accurately reflect current industry practices. A QA/QC analysis was performed for data gathering and input, documentation, and calculation. QA/QC checks are consistently conducted to minimize human error in the model calculations. EPA performs a thorough review of information associated with new studies to assess whether the assumptions in the Inventory are consistent with industry practices and whether new data is available that could be considered for updates to the estimates. As in previous years, EPA conducted early engagement and communication with stakeholders on updates prior to public review. EPA held stakeholder webinars on greenhouse gas data for oil and gas in September and November of 2021.

Recalculations Discussion

EPA received information and data related to the emission estimates through feedback on updates under consideration. In September 2021, EPA released a draft memorandum that discussed changes under consideration and requested stakeholder feedback on those changes. EPA then updated the memorandum to document the methodology implemented in the current Inventory.[84] The memorandum cited in the Recalculations Discussion below is, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Updates for Abandoned Oil and Gas Wells* (*Abandoned Wells* memo).

EPA updated the methodology to estimate abandoned wells activity data, including the population of abandoned wells and the fraction of abandoned wells that are plugged, as discussed in the *Abandoned Wells* memo. EPA did not update the emission factors. As in previous Inventories, the activity data methodology relies on Enverus data to: (1) estimate the population of abandoned oil and gas wells over the time series (along with data from historical references) and (2) estimate the fraction of abandoned wells that are plugged versus unplugged. This Inventory was recalculated with modifications to the Enverus data processing. Modifications to both steps are discussed here.

To estimate the population of abandoned oil wells and abandoned gas wells over the time series, EPA updated its method to rely on the gas-to-oil ratio (GOR) and the production type field within Enverus data to classify abandoned wells as oil versus gas wells. EPA used the production type field within the Enverus wells dataset only to apportion dry wells to oil and gas wells. The production type field was used in the previous (2021) Inventory to apportion dry wells, but for Inventories prior to the 2021 submission, only the GOR was used to assign abandoned wells as oil and gas wells.

To estimate the fraction of plugged and unplugged abandoned wells, EPA used the updated plugging status assignments for Enverus well status codes (see the *Abandoned Wells* memo) and assumed that all historical wells that are not captured in the Enverus wells dataset are unplugged. EPA first analyzed the Enverus dataset and determined that 58 percent of abandoned wells within Enverus are plugged. EPA then incorporated the historical well population (approximately 1.2 million wells) and assumed all historical wells are unplugged, resulting in an estimate of 41 percent of abandoned wells plugged (that percent is applied to year 2020 in the Inventory).

The Methodology and Time-Series Consistency section above includes tables with the updated plugged and unplugged abandoned well counts, reflecting the updates discussed here.

EPA received stakeholder feedback on the updates. A stakeholder recommended that the production type field within the Enverus dataset should be used to apportion wells that would otherwise be classified as dry wells (based on using the gas-to-oil ratio) into the classification of abandoned oil or abandoned gas wells, which was implemented in the final Inventory. The stakeholder suggested dry wells may be double counted and noted that some dry holes are plugged. The stakeholder also indicated that it may not be appropriate to assume all abandoned wells not captured within the Enverus dataset are unplugged. The stakeholder recommended using the "western US" emission factor from the Townsend-Small et al. study for areas outside of Appalachia, instead of the national average currently applied. Additionally, a stakeholder suggested that emissions from abandoned wells are underestimated.

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[84] Stakeholder materials including draft and final memoranda for the current (i.e., 1990 to 2020) Inventory are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

As an outcome of these revisions, calculated abandoned oil well CH_4 emissions decreased by an average of 6 percent across the time series and increased by 6 percent in 2019, compared to the values in the previous Inventory. Abandoned gas well CH_4 emissions increased by an average of 5 percent across the time series and increased by 6 percent in 2019, compared the to the previous Inventory.

Planned Improvements

EPA will continue to assess new data and stakeholder feedback on considerations (such as disaggregation of the well population into regions other than Appalachia and non-Appalachia, and emission factor data from regions not included in the measurement studies on which current emission factors are based) to improve the abandoned well count estimates and emission factors.

3.9 International Bunker Fuels (CRF Source Category 1: Memo Items)

Emissions resulting from the combustion of fuels used for international transport activities, termed international bunker fuels under the UNFCCC, are not included in national emission totals, but are reported separately based upon location of fuel sales. The decision to report emissions from international bunker fuels separately, instead of allocating them to a particular country, was made by the Intergovernmental Negotiating Committee in establishing the Framework Convention on Climate Change.[85] These decisions are reflected in the IPCC methodological guidance, including IPCC (2006), in which countries are requested to report emissions from ships or aircraft that depart from their ports with fuel purchased within national boundaries and are engaged in international transport separately from national totals (IPCC 2006).[86]

Two transport modes are addressed under the IPCC definition of international bunker fuels: aviation and marine.[87] Greenhouse gases emitted from the combustion of international bunker fuels, like other fossil fuels, include CO_2, CH_4 and N_2O for marine transport modes, and CO_2 and N_2O for aviation transport modes. Emissions from ground transport activities—by road vehicles and trains—even when crossing international borders are allocated to the country where the fuel was loaded into the vehicle and, therefore, are not counted as bunker fuel emissions.

The *2006 IPCC Guidelines* distinguish between three different modes of air traffic: civil aviation, military aviation, and general aviation. Civil aviation comprises aircraft used for the commercial transport of passengers and freight, military aviation comprises aircraft under the control of national armed forces, and general aviation applies to recreational and small corporate aircraft. The *2006 IPCC Guidelines* further define international bunker fuel use from civil aviation as the fuel combusted for civil (e.g., commercial) aviation purposes by aircraft arriving or departing on international flight segments. However, as mentioned above, and in keeping with the *2006 IPCC Guidelines*, only the fuel purchased in the United States and used by aircraft taking-off (i.e., departing) from the United States are reported here. The standard fuel used for civil and military aviation is kerosene-type jet fuel, while the typical fuel used for general aviation is aviation gasoline.[88]

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[85] See report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the work of its ninth session, held at Geneva from 7 to 18 February 1994 (A/AC.237/55, annex I, para. 1c).

[86] Note that the definition of international bunker fuels used by the UNFCCC differs from that used by the International Civil Aviation Organization.

[87] Most emission related international aviation and marine regulations are under the rubric of the International Civil Aviation Organization (ICAO) or the International Maritime Organization (IMO), which develop international codes, recommendations, and conventions, such as the International Convention of the Prevention of Pollution from Ships (MARPOL).

[88] Naphtha-type jet fuel was used in the past by the military in turbojet and turboprop aircraft engines.

Emissions of CO_2 from aircraft are essentially a function of fuel consumption. Nitrous oxide emissions also depend upon engine characteristics, flight conditions, and flight phase (i.e., take-off, climb, cruise, decent, and landing). Recent data suggest that little or no CH_4 is emitted by modern engines (Anderson et al. 2011), and as a result, CH_4 emissions from this category are reported as zero. In jet engines, N_2O is primarily produced by the oxidation of atmospheric nitrogen, and the majority of emissions occur during the cruise phase.

International marine bunkers comprise emissions from fuels burned by ocean-going ships of all flags that are engaged in international transport. Ocean-going ships are generally classified as cargo and passenger carrying, military (i.e., U.S. Navy), fishing, and miscellaneous support ships (e.g., tugboats). For the purpose of estimating greenhouse gas emissions, international bunker fuels are solely related to cargo and passenger carrying vessels, which is the largest of the four categories, and military vessels. Two main types of fuels are used on sea-going vessels: distillate diesel fuel and residual fuel oil. Carbon dioxide is the primary greenhouse gas emitted from marine shipping.

Overall, aggregate greenhouse gas emissions in 2020 from the combustion of international bunker fuels from both aviation and marine activities were 70.3 MMT CO_2 Eq., or 32.8 percent below emissions in 1990 (see Table 3-104 and Table 3-105). Emissions from international flights and international shipping voyages departing from the United States have increased by 4.1 percent and decreased by 54.4 percent, respectively, since 1990. The majority of these emissions were in the form of CO_2; however, small amounts of CH_4 (from marine transport modes) and N_2O were also emitted.

Table 3-104: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (MMT CO_2 Eq.)

Gas/Mode	1990	2005	2016	2017	2018	2019	2020
CO_2	**103.6**	**113.3**	**116.7**	**120.2**	**122.2**	**116.1**	**69.6**
Aviation	38.2	60.2	74.1	77.8	80.9	80.8	39.8
Commercial	*30.0*	*55.6*	*70.8*	*74.5*	*77.7*	*77.6*	*36.7*
Military	*8.2*	*4.6*	*3.3*	*3.3*	*3.2*	*3.2*	*3.1*
Marine	65.4	53.1	42.6	42.4	41.3	35.4	29.9
CH_4	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	0.2	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	**0.9**	**1.0**	**1.0**	**1.1**	**1.1**	**1.0**	**0.6**
Aviation	0.4	0.6	0.7	0.7	0.8	0.8	0.4
Marine	0.5	0.4	0.3	0.3	0.3	0.3	0.2
Total	**104.7**	**114.4**	**117.8**	**121.3**	**123.4**	**117.2**	**70.3**

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Table 3-105: CO_2, CH_4, and N_2O Emissions from International Bunker Fuels (kt)

Gas/Mode	1990	2005	2016	2017	2018	2019	2020
CO_2	**103,634**	**113,328**	**116,682**	**120,192**	**122,179**	**116,132**	**69,638**
Aviation	38,205	60,221	74,128	77,764	80,853	80,780	39,781
Marine	65,429	53,107	42,554	42,428	41,325	35,351	29,857
CH_4	**7**	**5**	**4**	**4**	**4**	**4**	**3**
Aviation	NO	NO	NO	NO	NO	NO	NO
Marine	7	5	4	4	4	4	3
N_2O	**3**	**3**	**3**	**4**	**4**	**3**	**2**
Aviation	1	2	2	2	3	3	1
Marine	2	1	1	1	1	1	1

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Includes aircraft cruise altitude emissions.

Methodology and Time-Series Consistency

Emissions of CO_2 were estimated by applying C content and fraction oxidized factors to fuel consumption activity data. This approach is analogous to that described under Section 3.1 – CO_2 from Fossil Fuel Combustion. Carbon content and fraction oxidized factors for jet fuel, distillate fuel oil, and residual fuel oil are the same as used for CO_2 from Fossil Fuel Combustion and are presented in Annex 2.1, Annex 2.2, and Annex 3.8 of this Inventory. Density conversions were taken from ASTM (1989) and USAF (1998). Heat content for distillate fuel oil and residual fuel oil were taken from EIA (2022) and USAF (1998), and heat content for jet fuel was taken from EIA (2022).

A complete description of the methodology and a listing of the various factors employed can be found in Annex 2.1. See Annex 3.8 for a specific discussion on the methodology used for estimating emissions from international bunker fuel use by the U.S. military.

Emission estimates for CH_4 and N_2O were calculated by multiplying emission factors by measures of fuel consumption by fuel type and mode. Emission factors used in the calculations of CH_4 and N_2O emissions were obtained from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), which is also referenced in the *2006 IPCC Guidelines* (IPCC 2006). For aircraft emissions, the following value, in units of grams of pollutant per kilogram of fuel consumed (g/kg), was employed: 0.1 for N_2O (IPCC 2006). For marine vessels consuming either distillate diesel or residual fuel oil the following values (g/MJ), were employed: 0.315 for CH_4 and 0.08 for N_2O. Activity data for aviation included solely jet fuel consumption statistics, while the marine mode included both distillate diesel and residual fuel oil.

Activity data on domestic and international aircraft fuel consumption were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 1990 and 2000 through 2020 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the *2006 IPCC Guidelines* (IPCC 2006).

International aviation CO_2 estimates for 1990 and 2000 through 2020 were obtained directly from FAA's AEDT model (FAA 2022). The radar-informed method that was used to estimate CO_2 emissions for commercial aircraft for 1990 and 2000 through 2020 was not possible for 1991 through 1999 because the radar dataset was not available for years prior to 2000. FAA developed Official Airline Guide (OAG) schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000, and 2010. Because fuel consumption and CO_2 emission estimates for years 1991 through 1999 are unavailable, consumption estimates for these years were calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on 2000 through 2005 data. See Annex 3.3 for more information on the methodology for estimating emissions from commercial aircraft jet fuel consumption.

Data on U.S. Department of Defense (DoD) aviation bunker fuels and total jet fuel consumed by the U.S. military was supplied by the Office of the Under Secretary of Defense (Installations and Environment), DoD. Estimates of the percentage of each Service's total operations that were international operations were developed by DoD. Military aviation bunkers included international operations, operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea. Military aviation bunker fuel emissions were estimated using military fuel and operations data synthesized from unpublished data from DoD's Defense Logistics Agency Energy (DLA Energy 2021). Together, the data allow the quantity of fuel used in military international operations to be estimated. Densities for each jet fuel type were obtained from a report from the U.S. Air Force (USAF 1998). Final jet fuel consumption estimates are presented in Table 3-106. See Annex 3.8 for additional discussion of military data.

Table 3-106: Aviation Jet Fuel Consumption for International Transport (Million Gallons)

Nationality	1990	2005	2016	2017	2018	2019	2020
U.S. and Foreign Carriers	3,155	5,858	7,452	7,844	8,178	8,170	3,859
U.S. Military	862	462	333	326	315	318	308
Total	**4,017**	**6,321**	**7,785**	**8,171**	**8,493**	**8,488**	**4,167**

Note: Totals may not sum due to independent rounding.

In order to quantify the civilian international component of marine bunker fuels, activity data on distillate diesel and residual fuel oil consumption by cargo or passenger carrying marine vessels departing from U.S. ports were collected for individual shipping agents on a monthly basis by the U.S. Customs and Border Protection. This information was then reported in unpublished data collected by the Foreign Trade Division of the U.S. Department of Commerce's Bureau of the Census (DOC 1991 through 2020) for 1990 through 2001, 2007 through 2020, and the Department of Homeland Security's Bunker Report for 2003 through 2006 (DHS 2008). Fuel consumption data for 2002 was interpolated due to inconsistencies in reported fuel consumption data. Activity data on distillate diesel consumption by military vessels departing from U.S. ports were provided by DLA Energy (2021). The total amount of fuel provided to naval vessels was reduced by 21 percent to account for fuel used while the vessels were not-underway (i.e., in port). Data on the percentage of steaming hours underway versus not underway were provided by the U.S. Navy. These fuel consumption estimates are presented in Table 3-107.

Table 3-107: Marine Fuel Consumption for International Transport (Million Gallons)

Fuel Type	1990	2005	2016	2017	2018	2019	2020
Residual Fuel Oil	4,781	3,881	3,011	2,975	2,790	2,246	1,964
Distillate Diesel Fuel & Other	617	444	534	568	684	702	461
U.S. Military Naval Fuels	522	471	314	307	285	281	296
Total	**5,920**	**4,796**	**3,858**	**3,850**	**3,759**	**3,229**	**2,721**

Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

Emission estimates related to the consumption of international bunker fuels are subject to the same uncertainties as those from domestic aviation and marine mobile combustion emissions; however, additional uncertainties result from the difficulty in collecting accurate fuel consumption activity data for international transport activities separate from domestic transport activities.[89] For example, smaller aircraft on shorter routes often carry sufficient fuel to complete several flight segments without refueling in order to minimize time spent at the airport gate or take advantage of lower fuel prices at particular airports. This practice, called tankering, when done on international flights, complicates the use of fuel sales data for estimating bunker fuel emissions. Tankering is less common with the type of large, long-range aircraft that make many international flights from the United States, however. Similar practices occur in the marine shipping industry where fuel costs represent a significant portion of overall operating costs and fuel prices vary from port to port, leading to some tankering from ports with low fuel costs.

Uncertainties exist with regard to the total fuel used by military aircraft and ships. Total aircraft and ship fuel use estimates were developed from DoD records, which document fuel sold to the DoD Components (e.g., Army, Department of Navy and Air Force) from the Defense Logistics Agency Energy. These data may not include fuel

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[89] See uncertainty discussions under section 3.1 CO_2 from Fossil Fuel Combustion.

used in aircraft and ships as a result of a Service procuring fuel from, selling fuel to, trading fuel with, or giving fuel to other ships, aircraft, governments, or other entities.

Additionally, there are uncertainties in historical aircraft operations and training activity data. Estimates for the quantity of fuel actually used in Navy and Air Force flying activities reported as bunker fuel emissions had to be estimated based on a combination of available data and expert judgment. Estimates of marine bunker fuel emissions were based on Navy vessel steaming hour data, which reports fuel used while underway and fuel used while not underway. This approach does not capture some voyages that would be classified as domestic for a commercial vessel. Conversely, emissions from fuel used while not underway preceding an international voyage are reported as domestic rather than international as would be done for a commercial vessel. There is uncertainty associated with ground fuel estimates for 1997 through 2020, including estimates for the quantity of jet fuel allocated to ground transportation. Small fuel quantities may have been used in vehicles or equipment other than that which was assumed for each fuel type.

There are also uncertainties in fuel end-uses by fuel type, emissions factors, fuel densities, diesel fuel sulfur content, aircraft and vessel engine characteristics and fuel efficiencies, and the methodology used to back-calculate the data set to 1990 using the original set from 1995. The data were adjusted for trends in fuel use based on a closely correlating, but not matching, data set. All assumptions used to develop the estimate were based on process knowledge, DoD data, and expert judgments. The magnitude of the potential errors related to the various uncertainties has not been calculated but is believed to be small. The uncertainties associated with future military bunker fuel emission estimates could be reduced through revalidation of assumptions based on data regarding current equipment and operational tempo, however, it is doubtful data with more fidelity exist at this time.

Although aggregate fuel consumption data have been used to estimate emissions from aviation, the recommended method for estimating emissions of gases other than CO_2 in the *2006 IPCC Guidelines* (IPCC 2006) is to use data by specific aircraft type, number of individual flights and, ideally, movement data to better differentiate between domestic and international aviation and to facilitate estimating the effects of changes in technologies. The IPCC also recommends that cruise altitude emissions be estimated separately using fuel consumption data, while landing and take-off (LTO) cycle data be used to estimate near-ground level emissions of gases other than CO_2.[90]

There is also concern regarding the reliability of the existing DOC (1991 through 2020) data on marine vessel fuel consumption reported at U.S. customs stations due to the significant degree of inter-annual variation.

QA/QC and Verification

In order to ensure the quality of the emission estimates from international bunker fuels, General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The Tier 2 procedures that were implemented involved checks specifically focusing on the activity data and emission factor sources and methodology used for estimating CO_2, CH_4, and N_2O emissions from international bunker fuels in the United States. Emission totals for the different sectors and fuels were compared and trends were investigated. No corrective actions were necessary.

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[90] U.S. aviation emission estimates for CO, NO_x, and NMVOCs are reported by EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends website, and reported under the Mobile Combustion section. It should be noted that these estimates are based solely upon LTO cycles and consequently only capture near ground-level emissions, which are more relevant for air quality evaluations. These estimates also include both domestic and international flights. Therefore, estimates reported under the Mobile Combustion section overestimate IPCC-defined domestic CO, NO_x, and NMVOC emissions by including landing and take-off (LTO) cycles by aircraft on international flights, but underestimate because they do not include emissions from aircraft on domestic flight segments at cruising altitudes.

Recalculations Discussion

The density for jet fuel was updated to 3.002 kilograms per gallon (EIA 2022) to improve consistency across estimates and data sources. This revision resulted in an average annual change of less than 0.05 MMT CO_2 Eq. in total emissions from international bunker fuels.

Planned Improvements

EPA will evaluate data availability to update the sources for densities, energy contents, and emission factors applied to estimate emissions from aviation and marine fuels. Many are from sources from the late 1990s, such as IPCC/UNEP/OECD/IEA (1997). Potential sources with more recent data include the International Maritime Organization (IMO) greenhouse gas emission inventory, International Air Transport Association (IATA)/ICAO greenhouse gas reporting system (CORSIA), and the EPA Greenhouse Gas Reporting Program (GHGRP) Technical Support Document for Petroleum Products. Specifically, EPA will evaluate data availability to support updating the heat contents and carbon contents of jet fuel with input from EIA.

A longer-term effort is underway to consider the feasibility of including data from a broader range of domestic and international sources for bunker fuels. Potential sources include the IMO greenhouse gas emission inventory, data from the U.S. Coast Guard on vehicle operation currently used in criteria pollutant modeling, data from the International Energy Agency (IEA), relevant updated FAA models to improve aviation bunker fuel estimates, and researching newly available marine bunker data.

3.10 Wood Biomass and Biofuels Consumption (CRF Source Category 1A)

The combustion of biomass fuels—such as wood, charcoal, and wood waste and biomass-based fuels such as ethanol, biogas, and biodiesel—generates CO_2 in addition to CH_4 and N_2O already covered in this chapter. In line with the reporting requirements for inventories submitted under the UNFCCC, CO_2 emissions from biomass combustion have been estimated separately from fossil fuel CO_2 emissions and are not directly included in the energy sector contributions to U.S. totals. In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net carbon fluxes from changes in biogenic C reservoirs in wooded or crop lands. For a more complete description of this methodological approach, see the Land Use, Land-Use Change, and Forestry chapter (Chapter 6), which accounts for the contribution of any resulting CO_2 emissions to U.S. totals within the Land Use, Land-Use Change, and Forestry sector's approach.

Therefore, CO_2 emissions from wood biomass and biofuel consumption are not included specifically in summing energy sector totals. However, they are presented here for informational purposes and to provide detail on wood biomass and biofuels consumption.

In 2020, total CO_2 emissions from the burning of woody biomass in the industrial, residential, commercial, and electric power sectors were approximately 202.1 MMT CO_2 Eq. (202,088 kt) (see Table 3-108 and Table 3-109). As the largest consumer of woody biomass, the industrial sector was responsible for 63.0 percent of the CO_2 emissions from this source. The residential sector was the second largest emitter, constituting 23.3 percent of the total, while the electric power and commercial sectors accounted for the remainder.

Table 3-108: CO_2 Emissions from Wood Consumption by End-Use Sector (MMT CO_2 Eq.)

End-Use Sector	1990		2005		2016	2017	2018	2019	2020
Industrial	135.3		136.3		138.3	135.4	134.4	132.1	127.2
Residential	59.8		44.3		45.8	44.3	54.1	56.1	47.2
Commercial	6.8		7.2		8.6	8.6	8.7	8.7	8.6

Electric Power	13.3	19.1	23.1	23.6	22.8	20.7	19.1
Total	**215.2**	**206.9**	**216.0**	**211.9**	**220.0**	**217.6**	**202.1**

Table 3-109: CO_2 Emissions from Wood Consumption by End-Use Sector (kt)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Industrial	135,348	136,269	138,339	135,386	134,417	132,069	127,242
Residential	59,808	44,340	45,841	44,257	54,070	56,135	47,177
Commercial	6,779	7,218	8,635	8,634	8,669	8,693	8,554
Electric Power	13,252	19,074	23,140	23,647	22,795	20,677	19,115
Total	**215,186**	**206,901**	**215,955**	**211,925**	**219,951**	**217,574**	**202,088**

Note: Totals may not sum due to independent rounding.

The transportation sector is responsible for most of the fuel ethanol consumption in the United States. Ethanol used for fuel is currently produced primarily from corn grown in the Midwest, but it can be produced from a variety of biomass feedstocks. Most ethanol for transportation use is blended with gasoline to create a 90 percent gasoline, 10 percent by volume ethanol blend known as E-10 or gasohol.

In 2020, the United States transportation sector consumed an estimated 994.6 trillion Btu of ethanol (95 percent of total), and as a result, produced approximately 68.1 MMT CO_2 Eq. (68,084 kt) (see Table 3-110 and Table 3-111) of CO_2 emissions. Smaller quantities of ethanol were also used in the industrial and commercial sectors. Ethanol fuel production and consumption has grown significantly since 1990 due to the favorable economics of blending ethanol into gasoline and federal policies that have encouraged use of renewable fuels.

Table 3-110: CO_2 Emissions from Ethanol Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation[a]	4.1	21.6	76.9	77.7	78.6	78.7	68.1
Industrial	0.1	1.2	1.8	1.9	1.4	1.6	1.6
Commercial	0.1	0.2	2.6	2.5	1.9	2.2	2.2
Total	**4.2**	**22.9**	**81.2**	**82.1**	**81.9**	**82.6**	**71.8**

[a] See Annex 3.2, Table A-76 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

Table 3-111: CO_2 Emissions from Ethanol Consumption (kt)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation[a]	4,059	21,616	76,903	77,671	78,603	78,739	68,084
Industrial	105	1,176	1,789	1,868	1,404	1,610	1,582
Commercial	63	151	2,558	2,550	1,910	2,229	2,182
Total	**4,227**	**22,943**	**81,250**	**82,088**	**81,917**	**82,578**	**71,847**

[a] See Annex 3.2, Table A-76 for additional information on transportation consumption of these fuels.

Note: Totals may not sum due to independent rounding.

The transportation sector is assumed to be responsible for all of the biodiesel consumption in the United States (EIA 2022). Biodiesel is currently produced primarily from soybean oil, but it can be produced from a variety of biomass feedstocks including waste oils, fats, and greases. Biodiesel for transportation use appears in low-level blends (less than 5 percent) with diesel fuel, high-level blends (between 6 and 20 percent) with diesel fuel, and 100 percent biodiesel (EIA 2020).

In 2020, the United States consumed an estimated 239.4 trillion Btu of biodiesel, and as a result, produced approximately 17.7 MMT CO_2 Eq. (17,678 kt) (see Table 3-112 and Table 3-113) of CO_2 emissions. Biodiesel production and consumption has grown significantly since 2001 due to the favorable economics of blending biodiesel into diesel and federal policies that have encouraged use of renewable fuels (EIA 2020). There was no measured biodiesel consumption prior to 2001 EIA (2022).

Table 3-112: CO_2 Emissions from Biodiesel Consumption (MMT CO_2 Eq.)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation[a]	NO	0.9	19.6	18.7	17.9	17.1	17.7

NO (Not Occurring)

[a] See Annex 3.2, Table A-76 for additional information on transportation consumption of these fuels.

Table 3-113: CO_2 Emissions from Biodiesel Consumption (kt)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation[a]	NO	856	19,648	18,705	17,936	17,080	17,678

NO (Not Occurring)

[a] See Annex 3.2, Table A-76 for additional information on transportation consumption of these fuels.

Methodology and Time-Series Consistency

Woody biomass emissions were estimated by applying two gross heat contents from EIA (Lindstrom 2006) to U.S. consumption data (EIA 2022) (see Table 3-114), provided in energy units for the industrial, residential, commercial, and electric power sectors. One heat content (16.95 MMBtu/MT wood and wood waste) was applied to the industrial sector's consumption, while the other heat content (15.43 MMBtu/MT wood and wood waste) was applied to the consumption data for the other sectors. An EIA emission factor of 0.434 MT C/MT wood (Lindstrom 2006) was then applied to the resulting quantities of woody biomass to obtain CO_2 emission estimates. The woody biomass is assumed to contain black liquor and other wood wastes, have a moisture content of 12 percent, and undergo complete combustion to be converted into CO_2.

The amount of ethanol allocated across the transportation, industrial, and commercial sectors was based on the sector allocations of ethanol-blended motor gasoline. The sector allocations of ethanol-blended motor gasoline were determined using a bottom-up analysis conducted by EPA, as described in the Methodology section of Fossil Fuel Combustion. Total U.S. ethanol consumption from EIA (2022) was allocated to individual sectors using the same sector allocations as ethanol-blended motor gasoline. The emissions from ethanol consumption were calculated by applying an emission factor of 18.67 MMT C/Qbtu (EPA 2010) to adjusted ethanol consumption estimates (see Table 3-115). The emissions from biodiesel consumption were calculated by applying an emission factor of 20.1 MMT C/Qbtu (EPA 2010) to U.S. biodiesel consumption estimates that were provided in energy units (EIA 2022) (see Table 3-116).[91]

Table 3-114: Woody Biomass Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Industrial	1,441.9	1,451.7	1,473.8	1,442.3	1,432.0	1,407.0	1,355.6
Residential	580.0	430.0	444.6	429.2	524.4	544.4	457.5
Commercial	65.7	70.0	83.7	83.7	84.1	84.3	83.0
Electric Power	128.5	185.0	224.4	229.3	221.1	200.5	185.4
Total	**2,216.2**	**2,136.7**	**2,226.5**	**2,184.6**	**2,261.5**	**2,236.2**	**2,081.4**

Note: Totals may not sum due to independent rounding.

Table 3-115: Ethanol Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation	59.3	315.8	1,123.4	1,134.6	1,148.2	1,150.2	994.6
Industrial	1.5	17.2	26.1	27.3	20.5	23.5	23.1

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[91] CO_2 emissions from biodiesel do not include emissions associated with the C in the fuel that is from the methanol used in the process. Emissions from methanol use and combustion are assumed to be accounted for under Non-Energy Use of Fuels. See Annex 2.3 – Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Commercial	0.9	2.2	37.4	37.2	27.9	32.6	31.9
Total	**61.7**	**335.1**	**1,186.9**	**1,199.1**	**1,196.6**	**1,206.3**	**1,049.5**

Note: Totals may not sum due to independent rounding.

Table 3-116: Biodiesel Consumption by Sector (Trillion Btu)

End-Use Sector	1990	2005	2016	2017	2018	2019	2020
Transportation	NO	11.6	266.1	253.3	242.9	231.3	239.4
Total	**NO**	**11.6**	**266.1**	**253.3**	**242.9**	**231.3**	**239.4**

NO (Not Occurring)

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

It is assumed that the combustion efficiency for woody biomass is 100 percent, which is believed to be an overestimate of the efficiency of wood combustion processes in the United States. Decreasing the combustion efficiency would decrease emission estimates for CO_2. Additionally, the heat content applied to the consumption of woody biomass in the residential, commercial, and electric power sectors is unlikely to be a completely accurate representation of the heat content for all the different types of woody biomass consumed within these sectors. Emission estimates from ethanol and biodiesel production are more certain than estimates from woody biomass consumption due to better activity data collection methods and uniform combustion techniques.

Recalculations Discussion

EIA (2022) revised approximate heat rates for electricity and the heat content of electricity for noncombustible renewable energy, which impacted wood energy consumption by the industrial sector from 2016 through 2019. In addition, EIA (2022) revised its methodology for calculating renewable diesel fuel consumption which impacts biofuel consumption. Between 2016 and 2019, revisions to biomass consumption resulted in an average annual increase of 0.5 MMT CO_2 Eq. (0.2 percent). Overall, revisions to biomass consumption resulted in an average annual increase of 0.1 MMT CO_2 Eq. (less than 0.05 percent) across the time series.

Planned Improvements

Future research will investigate the availability of data on woody biomass heat contents and carbon emission factors to see if there are newer, improved data sources available for these factors.

Currently, emission estimates from biomass and biomass-based fuels included in this Inventory are limited to woody biomass, ethanol, and biodiesel. Additional forms of biomass-based fuel consumption include biogas, the biogenic components of MSW, and other renewable diesel fuels. EPA will investigate additional forms of biomass-based fuel consumption, research the availability of relevant emissions factors, and integrate these into the Inventory as feasible. EPA will examine EIA data on biogas and other renewable diesel fuels to see if these fuel types can be included in future Inventories. EIA (2022) natural gas data already deducts biogas used in the natural gas supply, so no adjustments are needed to the natural gas fuel consumption data to account for biogas. Distillate fuel statistics are adjusted in this Inventory to remove other renewable diesel fuels as well as biodiesel. Sources of estimates for the biogenic fraction of MSW will be examined, including EPA's GHGRP, EIA data, and EPA MSW characterization data. Additionally, options for including "Other Renewable Fuels," as defined by EIA, will be evaluated.

The availability of facility-level combustion emissions through EPA's GHGRP will be examined to help better characterize the industrial sector's energy consumption in the United States and further classify woody biomass consumption by business establishments according to industrial economic activity type. Most methodologies used in EPA's GHGRP are consistent with IPCC, although for EPA's GHGRP, facilities collect detailed information specific to their operations according to detailed measurement standards, which may differ with the more aggregated data collected for the Inventory to estimate total, national U.S. emissions. In addition, and unlike the reporting requirements for this chapter under the UNFCCC reporting guidelines, some facility-level fuel combustion emissions reported under EPA's GHGRP may also include industrial process emissions.[92]

In line with UNFCCC reporting guidelines, fuel combustion emissions are included in this chapter, while process emissions are included in the Industrial Processes and Product Use chapter of this report. In examining data from EPA's GHGRP that would be useful to improve the emission estimates for the CO_2 from biomass combustion category, particular attention will also be made to ensure time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as reported in this Inventory. Additionally, analyses will focus on aligning reported facility-level fuel types and IPCC fuel types per the national energy statistics, ensuring CO_2 emissions from biomass are separated in the facility-level reported data, and maintaining consistency with national energy statistics provided by EIA. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[93]

Carbon dioxide emissions from biomass used in the electric power sector are calculated using woody biomass consumption data from EIA's *Monthly Energy Review* (EIA 2022), whereas non-CO_2 biomass emissions from the electric power sector are estimated by applying technology and fuel use data from EPA's Clean Air Market Acid Rain Program dataset (EPA 2022) to fuel consumption data from EIA (2022). There were significant discrepancies identified between the EIA woody biomass consumption data and the consumption data estimated using EPA's Acid Rain Program Dataset (see the Methodology section for CH_4 and N_2O from Stationary Combustion). EPA will continue to investigate this discrepancy in order to apply a consistent approach to both CO_2 and non-CO_2 emission calculations for woody biomass consumption in the electric power sector.

3.11 Energy Sources of Precursor Greenhouse Gas Emissions

In addition to the main greenhouse gases addressed above, energy-related activities are also sources of greenhouse gas precursors. The reporting requirements of the UNFCCC[94] request that information be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., tropospheric ozone) and atmospheric aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from energy-related activities from 1990 to 2020 are reported in Table 3-117.

Table 3-117: NO_x, CO, NMVOC, and SO_2 Emissions from Energy-Related Activities (kt)

Gas/Activity	1990	2005	2016	2017	2018	2019	2020
NO_x	**21,106**	**16,602**	**8,268**	**7,883**	**7,456**	**6,962**	**6,471**
Fossil Fuel Combustion	20,885	16,153	7,595	7,246	6,819	6,325	5,834
Transportation	*10,862*	*10,295*	*4,739*	*4,519*	*4,153*	*3,788*	*3,422*
Industrial	*2,559*	*1,515*	*890*	*859*	*859*	*859*	*859*
Electric Power Sector	*6,045*	*3,434*	*1,234*	*1,049*	*987*	*859*	*733*
Commercial	*671*	*490*	*440*	*537*	*537*	*537*	*537*

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[92] See https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2.

[93] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[94] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Residential	*749*	*418*	*292*	*283*	*283*	*283*	*283*
Petroleum and Natural Gas Systems	137	301	557	530	530	530	530
Incineration of Waste	82	128	80	71	71	71	71
Other Energy	2	20	37	35	35	35	35
International Bunker Fuels[a]	*1,953*	*1,699*	*1,464*	*1,475*	*1,456*	*1,290*	*1,019*
CO	**125,640**	**64,985**	**34,461**	**33,401**	**32,392**	**31,384**	**30,376**
Fossil Fuel Combustion	124,360	63,263	32,479	31,634	30,626	29,617	28,609
Transportation	*119,360*	*58,615*	*28,789*	*27,942*	*26,934*	*25,926*	*24,918*
Residential	*3,668*	*2,856*	*2,215*	*2,291*	*2,291*	*2,291*	*2,291*
Industrial	*797*	*1,045*	*771*	*736*	*736*	*736*	*736*
Electric Power Sector	*329*	*582*	*575*	*532*	*532*	*532*	*532*
Commercial	*205*	*166*	*128*	*133*	*133*	*133*	*133*
Petroleum and Natural Gas Systems	299	294	560	546	546	546	546
Incineration of Waste	978	1,403	1,375	1,175	1,175	1,175	1,175
Other Energy	3	24	47	46	46	46	46
International Bunker Fuels[a]	*102*	*131*	*147*	*153*	*158*	*154*	*101*
NMVOCs	**12,612**	**7,345**	**6,022**	**5,664**	**5,491**	**5,318**	**5,145**
Fossil Fuel Combustion	11,836	6,594	3,443	3,293	3,120	2,947	2,774
Transportation	*10,932*	*5,724*	*2,873*	*2,728*	*2,555*	*2,382*	*2,209*
Residential	*686*	*518*	*322*	*319*	*319*	*319*	*319*
Commercial	*10*	*188*	*117*	*116*	*116*	*116*	*116*
Industrial	*165*	*120*	*101*	*101*	*101*	*101*	*101*
Electric Power Sector	*43*	*44*	*31*	*29*	*29*	*29*	*29*
Petroleum and Natural Gas Systems	552	497	2,397	2,205	2,205	2,205	2,205
Incineration of Waste	222	241	121	109	109	109	109
Other Energy	2	13	62	57	57	57	57
International Bunker Fuels[a]	*57*	*6,594*	*49*	*50*	*50*	*46*	*34*
SO$_2$	**19,628**	**12,364**	**2,439**	**1,794**	**1,701**	**1,433**	**1,270**
Fossil Fuel Combustion	19,200	12,159	2,327	1,686	1,594	1,326	1,163
Electric Power Sector	*14,433*	*9,439*	*1,819*	*1,257*	*1,167*	*902*	*742*
Industrial	*3,221*	*1,574*	*389*	*342*	*342*	*342*	*342*
Transportation	*793*	*619*	*57*	*48*	*45*	*42*	*39*
Commercial	*589*	*370*	*43*	*28*	*28*	*28*	*28*
Residential	*165*	*158*	*18*	*12*	*12*	*12*	*12*
Petroleum and Natural Gas Systems	387	177	85	82	82	82	82
Incineration of Waste	38	25	24	22	22	22	22
Other Energy	3	3	3	3	3	3	3
International Bunker Fuels[a]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*

NA (Not Applicable)

[a] These values are presented for informational purposes only and are not included in totals.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2021a). For Table 3-117, NEI reported emissions of CO, NO$_x$, NMVOCs, and SO$_2$ are recategorized from NEI Tier 1/Tier 2 source categories to those more closely aligned with IPCC categories, based on EPA (2022).[95] NEI Tier 1 emission categories related to the energy sector categories in

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[95] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. Reported NEI emission estimates are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For this report, EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO$_x$, SO$_2$, and NMVOCs) from NEI Tier 1/Tier 2 categories

this report include: fuel combustion for electric utilities, industrial, and other; petroleum and related industries; highway vehicles; off-highway; and waste disposal and recycling (incineration, open burning). As described in detail in the NEI Technical Support Documentation (TSD) (EPA 2021b), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends website (EPA 2021a; EPA 2021b). Updates to historical activity data are documented in NEI's TSD (EPA 2021b). No quantitative estimates of uncertainty were calculated for this source category.

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to better align with NIR source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.6 for more information on this mapping.

4. Industrial Processes and Product Use

The Industrial Processes and Product Use (IPPU) chapter includes greenhouse gas emissions occurring from industrial processes and from the use of greenhouse gases in products. The industrial processes and product use categories included in this chapter are presented in Figure 4-1 and Figure 4-2. Greenhouse gas emissions from industrial processes can occur in two different ways. First, they may be generated and emitted as the byproducts of various non-energy-related industrial activities. Second, they may be emitted due to their use in manufacturing processes or by end-consumers. Combustion-related energy use emissions from industry are reported in Chapter 3, Energy.

In the case of byproduct emissions, the emissions are generated by an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically or physically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated greenhouse gases (e.g., HFC-23). The greenhouse gas byproduct generating processes included in this chapter include iron and steel production and metallurgical coke production, cement production, petrochemical production, ammonia production, lime production, other process uses of carbonates (e.g., flux stone, flue gas desulfurization, and soda ash consumption not associated with glass manufacturing), nitric acid production, adipic acid production, urea consumption for non-agricultural purposes, aluminum production, HCFC-22 production, glass production, soda ash production, ferroalloy production, titanium dioxide production, caprolactam production, zinc production, phosphoric acid production, lead production, and silicon carbide production and consumption.

Greenhouse gases that are used in manufacturing processes or by end-consumers include man-made compounds such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). The present contribution of HFCs, PFCs, SF_6, and NF_3 gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to persist in the atmosphere long after they were first released. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Use of HFCs is growing rapidly since they are the primary substitutes for ozone depleting substances (ODS), which are being phased-out under the Montreal Protocol on Substances that Deplete the Ozone Layer. Hydrofluorocarbons, PFCs, SF_6, and NF_3 are employed and emitted by a number of other industrial sources in the United States, such as electronics industry, electric power transmission and distribution, aluminum production, and magnesium metal production and processing. Carbon dioxide is also consumed and emitted through various end-use applications. In addition, nitrous oxide is used in and emitted by the electronics industry and anesthetic and aerosol applications.

In 2020, IPPU generated emissions of 376.4 million metric tons of CO_2 equivalent (MMT CO_2 Eq.), or 6.3 percent of total U.S. greenhouse gas emissions.[1] Carbon dioxide emissions from all industrial processes were 163.6 MMT CO_2

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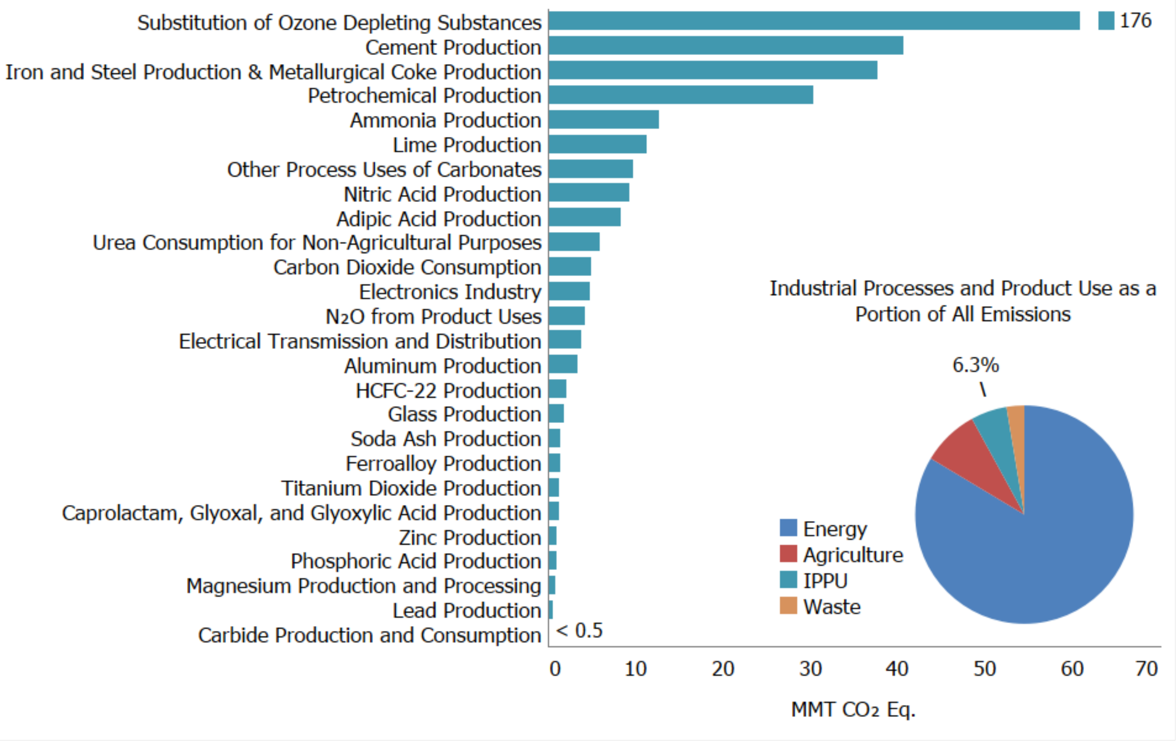
[1] Emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from U.S. Territories to the extent of which industries are occurring.

Eq. (163,571 kt CO_2) in 2020, or 3.5 percent of total U.S. CO_2 emissions. Methane emissions from industrial processes resulted in emissions of approximately 0.3 MMT CO_2 Eq. (14 kt CH_4) in 2020, which was 0.1 percent of U.S. CH_4 emissions. Nitrous oxide emissions from IPPU were 23.3 MMT CO_2 Eq. (78 kt N_2O) in 2020, or 5.5 percent of total U.S. N_2O emissions. In 2020 combined emissions of HFCs, PFCs, SF_6, and NF_3 totaled 189.2 MMT CO_2 Eq. Total emissions from IPPU in 2020 were 8.7 percent more than 1990 emissions. Total emissions from IPPU remained relatively constant between 2019 and 2020, decreasing by 0.8 percent due to offsetting trends within the sector. Some industrial processes and product use categories experienced decreases due to impacts from the coronavirus (COVID-19) pandemic (e.g., iron and steel production and lime production), while other categories experienced increases in emissions from 2019 to 2020 (e.g., ammonia production and the substitution of ozone depleting substances). More information on emissions of greenhouse gas precursors emissions that also result from IPPU are presented in Section 4.27 of this chapter.

Figure 4-1: 2020 Industrial Processes and Product Use Sector Greenhouse Gas Sources



The increase in overall IPPU emissions since 1990 reflects a range of emission trends among the emission sources, as shown in Figure 4-2. Emissions resulting from most types of metal production have declined significantly since 1990, largely due to production shifting to other countries, but also due to transitions to less-emissive methods of production (in the case of iron and steel) and to improved practices (in the case of PFC emissions from aluminum production). Carbon dioxide and CH_4 emissions from many chemical production sources have either decreased or not changed significantly since 1990, with the exception of petrochemical production, ammonia production, urea consumption for non-agricultural purposes, and carbon dioxide consumption, which has steadily increased. Emissions from mineral sources have either increased (e.g., cement production) or not changed significantly (e.g., glass and lime production) since 1990 but largely follow economic cycles. Hydrofluorocarbon emissions from the substitution of ODS have increased drastically since 1990 and are the largest source of IPPU emissions (46.8 percent in 2020), while the emissions of HFCs, PFCs, SF_6, and NF_3 from other sources have generally declined. Nitrous oxide emissions from the production of nitric acid have decreased. Some emission sources (e.g., adipic acid) exhibit varied interannual trends. Trends are explained further within each emission source category throughout the chapter.

Figure 4-2: Trends in Industrial Processes and Product Use Sector Greenhouse Gas Sources

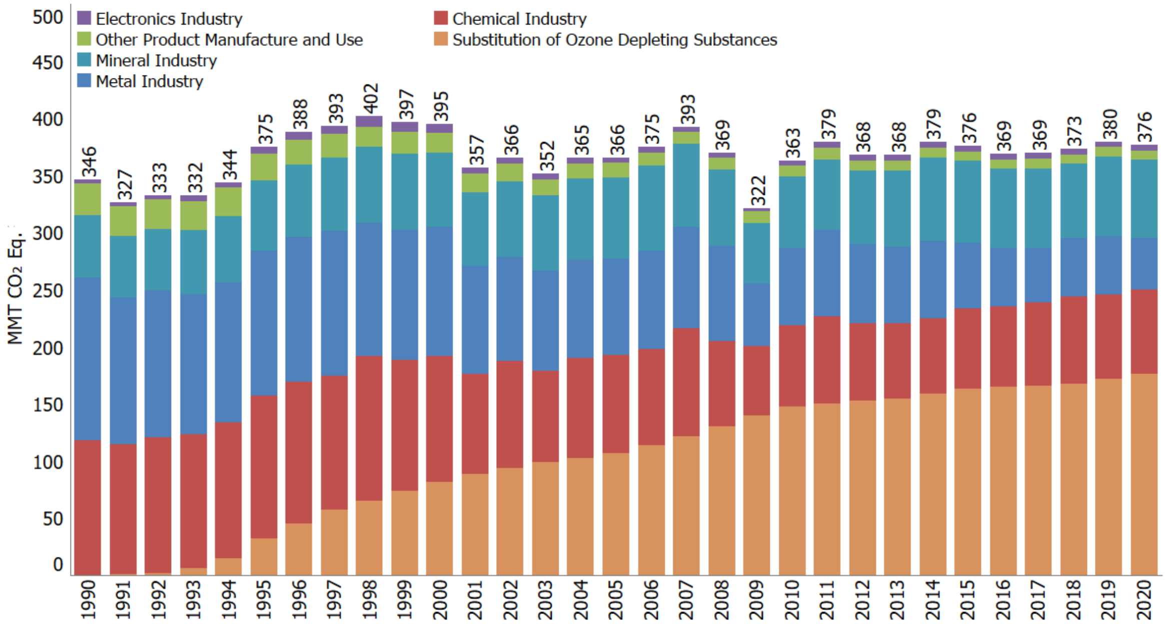


Table 4-1 summarizes emissions for the IPPU chapter in MMT CO_2 Eq. using *IPCC Fourth Assessment Report* (AR4) GWP values, following the requirements of the current United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories (IPCC 2007).[2] Unweighted native gas emissions in kt are also provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the Common Reporting Format (CRF) tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, SF_6, and NF_3.

Each year, some emission and sink estimates in the IPPU sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate. Key updates to this year's inventory include revisions to the Glass Production methodology to use more complete GHGRP activity data for the years 2010 through 2020; updated activity data for Iron and Steel Production (e.g., updated coke production values, updated scrap steel consumption for EAF steel production, scrap steel consumption for BOF steel production, and pellet consumption in blast furnace); updates to emission estimates from Urea Consumption for Non-Agricultural purposes driven by revisions to quantities of urea applied, urea imports, and urea exports; and revisions to CO_2 from Magnesium Production and Processing (e.g., the inclusion of CO_2 emissions from permanent mold, wrought, and anode production for the time series, the inclusion of CO_2 emissions from sand casting for the years 1990 through 2010) and Other Process Use of Carbonates (e.g., moving CO_2 emissions from the use of dolomite in primary magnesium metal production from Other Process Uses of Carbonates to Magnesium Production and Processing). Together, these updates increased greenhouse gas emissions an average of 0.7 MMT CO_2 Eq. (0.2 percent) across the time series.

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[2] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Table 4-1: Emissions from Industrial Processes and Product Use (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**213.0**	**194.4**	**166.0**	**164.7**	**165.1**	**171.2**	**163.6**
Iron and Steel Production & Metallurgical Coke Production	104.7	70.1	43.6	40.6	42.6	43.1	37.7
Iron and Steel Production	*99.1*	*66.2*	*41.0*	*38.6*	*41.3*	*40.1*	*35.4*
Metallurgical Coke Production	*5.6*	*3.9*	*2.6*	*2.0*	*1.3*	*3.0*	*2.3*
Cement Production	33.5	46.2	39.4	40.3	39.0	40.9	40.7
Petrochemical Production	21.6	27.4	28.1	28.9	29.3	30.7	30.0
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7
Lime Production	11.7	14.6	12.6	12.9	13.1	12.1	11.3
Other Process Uses of Carbonates	6.2	7.5	10.8	9.9	7.4	9.8	9.8
Urea Consumption for Non-Agricultural Purposes	3.8	3.7	5.3	5.2	6.0	6.0	6.0
Carbon Dioxide Consumption	1.5	1.4	4.6	4.6	4.1	4.9	5.0
Glass Production	2.3	2.4	2.1	2.0	2.0	1.9	1.9
Aluminum Production	6.8	4.1	1.3	1.2	1.5	1.9	1.7
Soda Ash Production	1.4	1.7	1.7	1.8	1.7	1.8	1.5
Ferroalloy Production	2.2	1.4	1.8	2.0	2.1	1.6	1.4
Titanium Dioxide Production	1.2	1.8	1.7	1.7	1.5	1.5	1.3
Zinc Production	0.6	1.0	0.8	0.9	1.0	1.0	1.0
Phosphoric Acid Production	1.5	1.3	1.0	1.0	0.9	0.9	0.9
Lead Production	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Carbide Production and Consumption	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Magnesium Production and Processing	0.1	+	+	+	+	+	+
CH_4	**0.3**	**0.1**	**0.3**	**0.3**	**0.3**	**0.4**	**0.3**
Petrochemical Production	0.2	0.1	0.2	0.3	0.3	0.3	0.3
Carbide Production and Consumption	+	+	+	+	+	+	+
Ferroalloy Production	+	+	+	+	+	+	+
Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	+	+
Iron and Steel Production	*+*	*+*	*+*	*+*	*+*	*+*	*+*
Metallurgical Coke Production	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
N_2O	**33.3**	**24.9**	**23.4**	**22.7**	**26.0**	**21.1**	**23.3**
Nitric Acid Production	12.1	11.3	10.1	9.3	9.6	10.0	9.3
Adipic Acid Production	15.2	7.1	7.1	7.5	10.5	5.3	8.3
N_2O from Product Uses	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Caprolactam, Glyoxal, and Glyoxylic Acid Production	1.7	2.1	1.7	1.5	1.4	1.4	1.2
Electronics Industry	+	0.1	0.2	0.3	0.3	0.2	0.3
HFCs	**46.5**	**127.4**	**168.3**	**171.1**	**171.0**	**175.9**	**178.8**
Substitution of Ozone Depleting Substances[a]	0.2	107.2	165.1	165.5	167.3	171.8	176.2
HCFC-22 Production	46.1	20.0	2.8	5.2	3.3	3.7	2.1
Electronics Industry	0.2	0.2	0.3	0.4	0.4	0.4	0.4
Magnesium Production and Processing	0.0	0.0	0.1	0.1	0.1	0.1	0.1
PFCs	**24.3**	**6.7**	**4.4**	**4.2**	**4.8**	**4.6**	**4.4**
Electronics Industry	2.8	3.3	3.0	3.0	3.1	2.8	2.7
Aluminum Production	21.5	3.4	1.4	1.1	1.6	1.8	1.7

Substitution of Ozone Depleting Substances	0.0	+	+	+	0.1	0.1	0.1
Electrical Transmission and Distribution	0.0	+	+	+	0.0	+	+
SF_6	**28.8**	**11.8**	**6.0**	**5.9**	**5.7**	**5.9**	**5.4**
Electrical Transmission and Distribution	23.2	8.3	4.1	4.2	3.8	4.2	3.8
Magnesium Production and Processing	5.2	2.7	1.1	1.0	1.0	0.9	0.9
Electronics Industry	0.5	0.7	0.8	0.7	0.8	0.8	0.7
NF_3	**+**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Electronics Industry	+	0.5	0.6	0.6	0.6	0.6	0.6
Total	**346.2**	**365.9**	**369.0**	**369.4**	**373.4**	**379.5**	**376.4**

Note: Totals may not sum due to independent rounding.

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Small amounts of PFC emissions also result from this source.

Table 4-2: Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**213,017**	**194,389**	**165,969**	**164,660**	**165,086**	**171,154**	**163,571**
Iron and Steel Production & Metallurgical Coke Production	104,737	70,076	43,621	40,566	42,627	43,090	37,731
Iron and Steel Production	*99,129*	*66,156*	*40,979*	*38,587*	*41,345*	*40,084*	*35,407*
Metallurgical Coke Production	*5,608*	*3,921*	*2,643*	*1,978*	*1,282*	*3,006*	*2,324*
Cement Production	33,484	46,194	39,439	40,324	38,971	40,896	40,688
Petrochemical Production	21,611	27,383	28,110	28,890	29,314	30,702	30,011
Ammonia Production	13,047	9,177	10,245	11,112	12,163	12,272	12,717
Lime Production	11,700	14,552	12,630	12,882	13,106	12,112	11,299
Other Process Uses of Carbonates	6,233	7,459	10,813	9,869	7,351	9,848	9,794
Urea Consumption for Non-Agricultural Purposes	3,784	3,653	5,330	5,182	6,030	6,044	5,983
Carbon Dioxide Consumption	1,472	1,375	4,640	4,580	4,130	4,870	4,970
Glass Production	2,291	2,432	2,119	2,011	1,989	1,938	1,857
Aluminum Production	6,831	4,142	1,334	1,205	1,451	1,880	1,748
Soda Ash Production	1,431	1,655	1,723	1,753	1,714	1,792	1,461
Ferroalloy Production	2,152	1,392	1,796	1,975	2,063	1,598	1,377
Titanium Dioxide Production	1,195	1,755	1,662	1,688	1,541	1,474	1,340
Zinc Production	632	1,030	838	900	999	1,026	1,008
Phosphoric Acid Production	1,529	1,342	998	1,025	937	909	938
Lead Production	516	553	500	513	513	527	495
Carbide Production and Consumption	243	213	170	181	184	175	154
Magnesium Production and Processing	129	3	3	3	2	1	1
CH_4	**11**	**4**	**11**	**11**	**13**	**15**	**14**
Petrochemical Production	9	3	10	10	12	13	13
Carbide Production and Consumption	1	+	+	+	+	+	+
Ferroalloy Production	1	+	1	1	1	+	+
Iron and Steel Production & Metallurgical Coke Production	1	1	+	+	+	+	+
Iron and Steel Production	*1*	*1*	*+*	*+*	*+*	*+*	*+*
Metallurgical Coke Production	*0*	*0*	*0*	*0*	*0*	*0*	*0*

N_2O	**112**	**84**	**79**	**76**	**87**	**71**	**78**
Nitric Acid Production	41	38	34	31	32	34	31
Adipic Acid Production	51	24	24	25	35	18	28
N_2O from Product Uses	14	14	14	14	14	14	14
Caprolactam, Glyoxal, and Glyoxylic Acid Production	6	7	6	5	5	5	4
Electronics Industry	+	+	1	1	1	1	1
HFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M
HCFC-22 Production	3	1	+	+	+	+	+
Electronics Industry	M	M	M	M	M	M	M
Magnesium Production and Processing	NO	NO	+	+	+	+	+
PFCs	**M**	**M**	**M**	**M**	**M**	**M**	**M**
Electronics Industry	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances	NO	+	+	+	+	+	+
Electrical Transmission and Distribution	NO	+	+	+	NO	+	+
SF_6	**1**	**1**	**+**	**+**	**+**	**+**	**+**
Electrical Transmission and Distribution	1	+	+	+	+	+	+
Magnesium Production and Processing	+	+	+	+	+	+	+
Electronics Industry	+	+	+	+	+	+	+
NF_3	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Electronics Industry	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
M (Mixture of gases)
NO (Not Occurring)
[a] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding.

This chapter presents emission estimates calculated in accordance with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*2006 IPCC Guidelines*) and its refinements. For additional detail on IPPU sources that are not included in this Inventory report, please review Annex 5, Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included. These sources are not included due to various national circumstances, such as that emissions from a source may not currently occur in the United States, data are not currently available for those emission sources (e.g., ceramics, non-metallurgical magnesium production, glyoxal and glyoxylic acid production, CH_4 from direct reduced iron production), emissions are included elsewhere within the Inventory report, or data suggest that emissions are not significant (e.g., other various fluorinated gas emissions from other product uses). In terms of geographic scope, emissions reported in the IPPU chapter include those from all 50 states, including Hawaii and Alaska, as well as from District of Columbia and U.S. Territories to the extent to which industries are occurring. While most IPPU sources do not occur in U.S. Territories (e.g., electronics manufacturing does not occur in U.S. Territories), they are estimated and accounted for where they are known to occur (e.g., cement production, lime production, and electrical transmission and distribution). EPA will review this on an ongoing basis to ensure emission sources are included across all geographic areas if they occur. Information on planned improvements for specific IPPU source categories can be found in the Planned Improvements section of the individual source category.

In addition, as mentioned in the Energy chapter of this report (Box 3-5), fossil fuels consumed for non-energy uses for primary purposes other than combustion for energy (including lubricants, paraffin waxes, bitumen asphalt, and solvents) are reported in the Energy chapter. According to the *2006 IPCC Guidelines*, these non-energy uses of fossil fuels are to be reported under the IPPU, rather than the Energy sector; however, due to national circumstances regarding the allocation of energy statistics and carbon balance data, the United States reports these non-energy uses in the Energy chapter of this Inventory. Although emissions from these non-energy uses are reported in the Energy chapter, the methodologies used to determine emissions are compatible with the *2006 IPCC Guidelines* and are well documented and scientifically based. The methodologies used are described in Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels. The emissions are reported under the Energy chapter to improve transparency, report a more complete carbon balance, and avoid double counting. For example, only the emissions from the first use of lubricants and waxes are to be reported under the IPPU sector, and emissions from use of lubricants in 2-stroke engines and emissions from secondary use of lubricants and waxes in waste incineration with energy recovery are to be reported under the Energy sector. Reporting non-energy use emissions from only first use of lubricants and waxes under IPPU would involve making artificial adjustments to the non-energy use carbon balance and could potentially result in double counting of emissions. These artificial adjustments would also be required for asphalt and road oil and solvents (which are captured as part of petrochemical feedstock emissions) and could also potentially result in double counting of emissions. For more information, see the Methodology discussion in Section 3.1, CO_2 from Fossil Fuel Combustion, Section 3.2, Carbon Emitted from Non-Energy Uses of Fossil Fuels and Annex 2.3, Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels.

Finally, as stated in the Energy chapter, portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil—are reallocated to the IPPU chapter, as they are consumed during non-energy related industrial process activity. Emissions from uses of fossil fuels as feedstocks or reducing agents (e.g., petrochemical production, aluminum production, titanium dioxide, zinc production) are reported in the IPPU chapter, unless otherwise noted due to specific national circumstances. This approach is compatible with the *2006 IPCC Guidelines* and is well documented and scientifically based. The emissions from these feedstocks and reducing agents are reported under the IPPU chapter to improve transparency and to avoid double counting of emissions under both the Energy and IPPU sectors. More information on the methodology to adjust for these emissions within the Energy chapter is described in the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRF Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. Additional information is listed within each IPPU emission source in which this approach applies.

Box 4-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the IPPU chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from industrial processes and from the use of greenhouse gases in products.

QA/QC and Verification Procedures

For IPPU sources, a detailed QA/QC plan was developed and implemented for specific categories. This plan is consistent with the U.S. Inventory QA/QC plan outlined in Annex 8 but tailored to include specific procedures recommended for these sources. The IPPU QA/QC Plan does not replace the Inventory QA/QC Plan, but rather provides more context for the IPPU sector. The IPPU QA/QC Plan provides the completed QA/QC forms for each inventory reports, as well as, for certain source categories (e.g., key categories), more detailed documentation of quality control checks and recalculations due to methodological changes.

Two types of checks were performed using this plan: (1) general (Tier 1) procedures consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking, and archiving the data, supporting documents, and files; and (2) source category-specific (Tier 2) procedures that focus on checks and comparisons of the emission factors, activity data, and methodologies used for estimating emissions from the relevant industrial process and product use sources. Examples of these procedures include: checks to ensure that activity data and emission estimates are consistent with historical trends to identify significant changes; that, where possible, consistent and reputable data sources are used and specified across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets, units, and conversion factors are used where applicable. The IPPU QA/QC plan also checked for transcription errors in data inputs required for emission calculations, including activity data and emission factors; and confirmed that estimates were calculated and reported for all applicable and able portions of the source categories for all years.

For sources that use data from EPA's Greenhouse Gas Reporting Program (GHGRP), EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[3] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. See Box 4-2 below for more information on use of GHGRP data in this chapter.

General QA/QC procedures (Tier 1) and calculation-related QC (category-specific, Tier 2) have been performed for all IPPU sources. Consistent with the *2006 IPCC Guidelines*, additional category-specific QC procedures were performed for more significant emission categories (such as the comparison of reported consumption with modeled consumption using EPA's Greenhouse Gas Reporting Program (GHGRP) data within Substitution of Ozone Depleting Substances) or sources where significant methodological and data updates have taken place. The QA/QC implementation did not reveal any significant inaccuracies, and all errors identified were documented and corrected. Application of these procedures, specifically category-specific QC procedures and updates/improvements as a result of QA processes (expert, public, and UNFCCC technical expert reviews), are described further within respective source categories, in the Recalculations Discussion and Planned Improvement sections.

For most IPPU categories, activity data are obtained via aggregation of facility-level data from EPA's GHGRP (see Box 4-2 below and Annex 9), national commodity surveys conducted by U.S. Geological Survey National Minerals Information Center, U.S. Department of Energy (DOE), U.S. Census Bureau, and industry associations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Chemistry Council (ACC), and American Iron and Steel Institute (AISI) (specified within each source category). The emission factors used include those derived from the EPA's GHGRP and application of IPCC default factors. Descriptions of uncertainties and assumptions for activity data and emission factors are included within the uncertainty discussion sections for each IPPU source category.

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[3] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Box 4-2: Industrial Process and Product Use Data from EPA's Greenhouse Gas Reporting Program

EPA collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories. Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases.

In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year, but reporting is required for all facilities in some industries. Calendar year 2010 was the first year for which data were collected for facilities subject to 40 CFR Part 98, though some source categories first collected data for calendar year 2011. For more information, see Annex 9, Use of EPA Greenhouse Gas Reporting Program in Inventory.

EPA uses annual GHGRP data in a number of categories to improve the national estimates presented in this Inventory, consistent with IPCC guidelines (e.g., minerals, chemicals, product uses). Methodologies used in EPA's GHGRP are consistent with IPCC guidelines, including higher tier methods; however, it should be noted that the coverage and definitions for source categories (e.g., allocation of energy and IPPU emissions) in EPA's GHGRP may differ from those used in this Inventory in meeting the UNFCCC reporting guidelines (IPCC 2011) and is an important consideration when incorporating GHGRP data in the Inventory. In line with the UNFCCC reporting guidelines, the Inventory is a comprehensive accounting of all emissions from source categories identified in the *2006 IPCC Guidelines*. EPA has paid particular attention to ensuring both completeness and time-series consistency for major recalculations that have occurred from the incorporation of GHGRP data into these categories, consistent with *2006 IPCC Guidelines* and *IPCC Technical Bulletin on Use of Facility-Specific Data in National GHG Inventories.*[4]

For certain source categories in this Inventory (e.g., nitric acid production, lime production, cement production, petrochemical production, carbon dioxide consumption, ammonia production, and urea consumption for non-agricultural purposes), EPA has integrated data values that have been calculated by aggregating GHGRP data that are considered confidential business information (CBI) at the facility level. EPA, with industry engagement, has put forth criteria to confirm that a given data aggregation shields underlying CBI from public disclosure. EPA is only publishing data values that meet these aggregation criteria.[5] Specific uses of aggregated facility-level data are described in the respective methodological sections (e.g., including other sources using GHGRP data that is not aggregated CBI, such as aluminum, electronics industry, electrical transmission and distribution, HCFC-22 production, and magnesium production and processing.). For other source categories in this chapter, as indicated in the respective planned improvements sections,[6] EPA is continuing to analyze how facility-level GHGRP data may be used to improve the national estimates presented in this Inventory, giving particular consideration to ensuring time-series consistency and completeness.

Additionally, EPA's GHGRP has and will continue to enhance QA/QC procedures and assessment of uncertainties within the IPPU categories (see those categories for specific QA/QC details regarding the use of GHGRP data).

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[4] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[5] U.S. EPA Greenhouse Gas Reporting Program. Developments on Publication of Aggregated Greenhouse Gas Data, November 25, 2014. See http://www.epa.gov/ghgreporting/confidential-business-information-ghg-reporting.

[6] Ammonia Production, Glass Production, Lead Production, and Other Fluorinated Gas Production.

4.1 Cement Production (CRF Source Category 2A1)

Cement production is an energy- and raw material-intensive process that results in the generation of carbon dioxide (CO_2) both from the energy consumed in making the clinker precursor to cement and from the chemical process to make the clinker. Emissions from fuels consumed for energy purposes during the production of cement are accounted for in the Energy chapter.

During the clinker production process, the key reaction occurs when calcium carbonate ($CaCO_3$), in the form of limestone or similar rocks or in the form of cement kiln dust (CKD), is heated in a cement kiln at a temperature range of about 700 to 1,000 degrees Celsius (1,300 to 1,800 degrees Fahrenheit) to form lime (i.e., calcium oxide, or CaO) and CO_2 in a process known as calcination or calcining. The quantity of CO_2 emitted during clinker production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ heated in the clinker kiln forms one mole of CaO and one mole of CO_2. The CO_2 is vented to the atmosphere as part of the kiln exhaust:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Next, over a temperature range of 1000 to 1450 degrees Celsius, the CaO combines with alumina, iron oxide and silica that are also present in the clinker raw material mix to form hydraulically reactive compounds within white-hot semifused (sintered) nodules of clinker. Because these “sintering” reactions are highly exothermic, they produce few CO_2 process emissions. The clinker is then rapidly cooled to maintain quality and then very finely ground with a small amount of gypsum and potentially other materials (e.g., ground granulated blast furnace slag, etc.) to make portland and similar cements.

Masonry cement consists of plasticizers (e.g., ground limestone, lime, etc.) and portland cement, and the amount of portland cement used accounts for approximately 3 percent of total clinker production (USGS 2020). No additional emissions are associated with the production of masonry cement. Carbon dioxide emissions that result from the production of lime used to produce portland and masonry cement are included in Section 4.2 Lime Production (CRF Source Category 2A2).

Carbon dioxide emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States. Cement is produced in 34 states and Puerto Rico. Texas, California, Missouri, and Florida were the leading cement-producing states in 2020 and accounted for almost 45 percent of total U.S. production (USGS 2021). Clinker production in 2020 remained at relatively flat levels, compared to 2019 (EPA 2020; USGS 2021). In 2020, shipments of cement were essentially unchanged from 2019, and imports increased by about 7 percent compared to 2019. In 2020, U.S. clinker production totaled 78,200 kilotons (EPA 2021). The resulting CO_2 emissions were estimated to be 40.7 MMT CO_2 Eq. (40,688 kt) (see Table 4-3). In 2020 due to the COVID-19 pandemic, production of cement was temporarily idled in many localities and countries in response to the lockdowns imposed to limit the spread of COVID-19. Disruptions in the construction industry affected cement demand, and several plant openings and expansions were delayed due to the COVID-19 pandemic. The U.S. cement industry, however, showed no prolonged or widespread negative effects from the COVID-19 pandemic (USGS 2021).

Table 4-3: CO_2 Emissions from Cement Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	33.5	33,484
2005	46.2	46,194
2016	39.4	39,439
2017	40.3	40,324
2018	39.0	38,971
2019	40.9	40,896
2020	40.7	40,688

Greenhouse gas emissions from cement production, which are primarily driven by production levels, increased every year from 1991 through 2006 but decreased in the following years until 2009. Since 1990, emissions have increased by 22 percent. Emissions from cement production were at their lowest levels in 2009 (2009 emissions are approximately 28 percent lower than 2008 emissions and 12 percent lower than 1990) due to the economic recession and the associated decrease in demand for construction materials. Since 2010, emissions have increased by about 30 percent, due to increasing demand for cement. Cement continues to be a critical component of the construction industry; therefore, the availability of public and private construction funding, as well as overall economic conditions, have considerable impact on the level of cement production.

Methodology and Time-Series Consistency

Carbon dioxide emissions from cement production were estimated using the Tier 2 methodology from the *2006 IPCC Guidelines* as this is a key category. The Tier 2 methodology was used because detailed and complete data (including weights and composition) for carbonate(s) consumed in clinker production are not available,[7] and thus a rigorous Tier 3 approach is impractical. Tier 2 specifies the use of aggregated plant or national clinker production data and an emission factor, which is the product of the average lime fraction for clinker of 65 percent and a constant reflecting the mass of CO_2 released per unit of lime. The U.S. Geological Survey (USGS) mineral commodity expert for cement has confirmed that this is a reasonable assumption for the United States (Van Oss 2013a). This calculation yields an emission factor of 0.510 tons of CO_2 per ton of clinker produced, which was determined as follows:

Equation 4-1: *2006 IPCC Guidelines* Tier 1 Emission Factor for Clinker (precursor to Equation 2.4)

$$\mathrm{EF_{clinker}} = 0.650\ \mathrm{CaO} \times [(44.01\ \mathrm{g/mole\ CO_2}) \div (56.08\ \mathrm{g/mole\ CaO})] = 0.510\ \mathrm{tons\ CO_2/ton\ clinker}$$

During clinker production, some of the raw materials, partially reacted raw materials, and clinker enters the kiln line's exhaust system as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). To the degree that the CKD contains carbonate raw materials which are then calcined, there are associated CO_2 emissions. At some plants, essentially all CKD is directly returned to the kiln, becoming part of the raw material feed, or is likewise returned to the kiln after first being removed from the exhaust. In either case, the returned CKD becomes a raw material, thus forming clinker, and the associated CO_2 emissions are a component of those calculated for the clinker overall. At some plants, however, the CKD cannot be returned to the kiln because it is chemically unsuitable as a raw material or chemical issues limit the amount of CKD that can be so reused. Any clinker that cannot be returned to the kiln is either used for other (non-clinker) purposes or is landfilled. The CO_2 emissions attributable

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[7] As discussed further under "Planned Improvements," most cement-producing facilities that report their emissions to the GHGRP use CEMS to monitor combined process and fuel combustion emissions for kilns, making it difficult to quantify the process emissions on a facility-specific basis. In 2019, the percentage of facilities not using CEMS was 8 percent.

to the non-returned calcinated portion of the CKD are not accounted for by the clinker emission factor and thus a CKD correction factor should be applied to account for those emissions. The USGS reports the amount of CKD used to produce clinker, but no information is currently available on the total amount of CKD produced annually.[8] Because data are not currently available to derive a country-specific CKD correction factor, a default correction factor of 1.02 (2 percent) was used to account for CKD CO_2 emissions, as recommended by the IPCC (IPCC 2006).[9] Total cement production emissions were calculated by adding the emissions from clinker production and the emissions assigned to CKD.

Small amounts of impurities (i.e., not calcium carbonate) may exist in the raw limestone used to produce clinker. The proportion of these impurities is generally minimal, although a small amount (1 to 2 percent) of magnesium oxide (MgO) may be desirable as a flux. Per the IPCC Tier 2 methodology, a correction for MgO is not used, since the amount of MgO from carbonate is likely very small and the assumption of a 100 percent carbonate source of CaO already yields an overestimation of emissions (IPCC 2006).

The 1990 through 2012 activity data for clinker production were obtained from USGS (Van Oss 2013a, Van Oss 2013b). Clinker production data for 2013 were also obtained from USGS (USGS 2014). USGS compiled the data (to the nearest ton) through questionnaires sent to domestic clinker and cement manufacturing plants, including facilities in Puerto Rico. Clinker production values in the current Inventory report utilize GHGRP data for the years 2014 through 2020 (EPA 2021). Clinker production data are summarized in Table 4-4. Details on how this GHGRP data compares to USGS reported data can be found in the section on QA/QC and Verification.

Table 4-4: Clinker Production (kt)

Year	Clinker
1990	64,355
2005	88,783
2016	75,800
2017	77,500
2018	74,900
2019	78,600
2020	78,200

Notes: Clinker production from 1990 through 2020 includes Puerto Rico (relevant U.S. Territories).

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020. The methodology for cement production spliced activity data from two different sources: USGS for 1990 through 2013 and GHGRP starting in 2014. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

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[8] The USGS *Minerals Yearbook: Cement* notes that CKD values used for clinker production are likely underreported.

[9] As stated on p. 2.12 of the *2006 IPCC Guidelines*, Vol. 3, Chapter 2: "…As data on the amount of CKD produced may be scarce (except possibly for plant-level reporting), estimating emissions from lost CKD based on a default value can be considered good practice. The amount of CO_2 from lost CKD can vary, but ranges typically from about 1.5 percent (additional CO_2 relative to that calculated for clinker) for a modern plant to about 20 percent for a plant losing a lot of highly calcinated CKD (van Oss 2005). In the absence of data, the default CKD correction factor (CF_{ckd}) is 1.02 (i.e., add 2 percent to the CO_2 calculated for clinker). If no calcined CKD is believed to be lost to the system, the CKD correction factor will be 1.00 (van Oss 2005)…"

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw materials are $CaCO_3$, when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent; 65 percent is used as a representative value (Van Oss 2013a). This contributes to the uncertainty surrounding the emission factor for clinker which has an uncertainty range of ±5 percent with uniform densities (Van Oss 2013b). The amount of CO_2 from CKD loss can range from 1.5 to 8 percent depending upon plant specifications, and uncertainty was estimated at ±3 percent with uniform densities (Van Oss 2013b). Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of the total thickness. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated. EPA assigned default uncertainty bounds of ±3 percent for clinker production, based on expert judgment (Van Oss 2013b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-5. Based on the uncertainties associated with total U.S. clinker production, the CO_2 emission factor for clinker production, and the emission factor for additional CO_2 emissions from CKD, 2020 CO_2 emissions from cement production were estimated to be between 38.3 and 43.1 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 6 percent below and 6 percent above the emission estimate of 40.7 MMT CO_2 Eq.

Table 4-5: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Cement Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO_2	40.7	38.3	43.1	-6%	+6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

EPA relied upon the latest guidance from the IPCC on the use of facility-level data in national inventories and applied a category-specific QC process to compare activity data from EPA's GHGRP with existing data from USGS surveys. This was to ensure time-series consistency of the emission estimates presented in the Inventory. Total U.S. clinker production is assumed to have low uncertainty because facilities routinely measure this for economic reasons and because both USGS and GHGRP take multiple steps to ensure that reported totals are accurate. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the reporting industry (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews involving outside data checks) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[10] Facilities are also required to monitor and maintain records of monthly clinker production per section 98.84 of the GHGRP regulation (40 CFR 98.84).

EPA's GHGRP requires all facilities producing Portland cement to report greenhouse gas emissions, including CO_2 process emissions from each kiln, CO_2 combustion emissions from each kiln, CH_4 and N_2O combustion emissions from each kiln, and CO_2, CH_4, and N_2O emissions from each stationary combustion unit other than kilns (40 CFR Part 98 Subpart H). Source-specific quality control measures for the Cement Production category are included in section 98.84, Monitoring and QA/QC Requirements.

As mentioned above, EPA compares GHGRP clinker production data to the USGS clinker production data. For the year 2014 and 2020, USGS and GHGRP clinker production data showed a difference of approximately 1 percent. In 2018, the difference was approximately 3 percent. In 2015, 2016, 2017, and 2019, that difference was less than 1 percent between the two sets of activity data. This difference resulted in a difference in emissions compared to USGS data of about 0.1 MMT CO_2 Eq. in 2015, 2016, 2017, and 2019. The information collected by the USGS National Minerals Information Center surveys continue to be an important data source.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

EPA is continuing to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates for the Cement Production source category. Most cement production facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor and report CO_2 emissions, thus reporting combined process and combustion emissions from kilns. In implementing further improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon, in addition to category-specific QC methods recommended by the *2006 IPCC Guidelines*.[11] EPA's long-term improvement plan includes continued assessment of the feasibility of using additional GHGRP information beyond aggregation of reported facility-level clinker data, in particular disaggregating the combined process and combustion emissions reported using CEMS, to separately present national process and combustion emissions streams consistent with IPCC and UNFCCC guidelines. This long-term planned analysis is still in development and has not been applied for this current Inventory.

Finally, in response to feedback from Portland Cement Association (PCA) during the Public Review comment period of a previous Inventory, EPA plans to work with PCA to discuss additional long-term improvements to review methods and data used to estimate CO_2 emissions from cement production to account for organic material in the raw material and to discuss the carbonation that occurs across the duration of the cement product. Work includes identifying data and studies on the average carbon content for organic materials in kiln feed in the United States and CO_2 reabsorption rates via carbonation for various cement products. This information is not reported by facilities subject to GHGRP reporting.

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[10] See GHGRP Verification Fact Sheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[11] See IPCC Technical Bulletin on Use of Facility-Specific Data in National Greenhouse Gas Inventories http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

4.2 Lime Production (CRF Source Category 2A2 and 2H3)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Lime production involves three main processes: stone preparation, calcination, and hydration. Carbon dioxide (CO_2) is generated during the calcination stage, when limestone—consisting of calcium ($CaCO_3$) and/or magnesium ($MgCO_3$) carbonate—is roasted at high temperatures in a kiln to produce calcium oxide (CaO) and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere.

$$CaCO_3 \rightarrow CaO + CO_2$$

Some facilities, however, recover CO_2 generated during the production process for use in sugar refining and precipitated calcium carbonate (PCC) production.[12] PCC is used as a filler or coating in the paper, food, and plastic industries and is derived from reacting hydrated high-calcium quicklime with CO_2, a production process that does not result in net emissions of CO_2 to the atmosphere. Emissions from fuels consumed for energy purposes during the production of lime are included in the Energy chapter.

For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include CaO, or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

The current lime market is approximately distributed across five end-use categories, as follows: metallurgical uses, 34 percent; environmental uses, 30 percent; chemical and industrial uses, 21 percent; construction uses, 11 percent; and refractory dolomite, 1 percent (USGS 2020b). The major uses are in steel making, flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water treatment, as well as uses in mining, pulp and paper and precipitated calcium carbonate manufacturing. Lime is also used as a CO_2 scrubber, and there has been experimentation on the use of lime to capture CO_2 from electric power plants. Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from limestone consumption for FGD systems are reported under Section 4.4 Other Process Uses of Carbonate Production (CRF Source Category 2A4).

Emissions from lime production have increased and decreased over the time series depending on lime end-use markets – primarily the steel making industry and FGD systems for utility and industrial plants – and also energy costs. One significant change to lime end-use since 1990 has been the increase in demand for lime for FGD at coal-fired electric power plants, which can be attributed to compliance with sulfur dioxide (SO_2) emission regulations of the Clean Air Act Amendments of 1990. Phase I went into effect on January 1, 1995, followed by Phase II on January 1, 2000. To supply lime for the FGD market, the lime industry installed more than 1.8 million tons per year of new capacity by the end of 1995 (USGS 1996). The need for air pollution controls continued to drive the FGD lime market, which had doubled between 1990 and 2019 (USGS 1991 and 2020d).

The U.S. lime industry temporarily shut down some individual gas-fired kilns and, in some case, entire lime plants during 2000 and 2001, due to significant increases in the price of natural gas. Lime production continued to decrease in 2001 and 2002, a result of lower demand from the steel making industry, lime's largest end-use market, when domestic steel producers were affected by low priced imports and slowing demand (USGS 2002).

Emissions from lime production increased and then peaked in 2006 at approximately 30.3 percent above 1990 levels, due to strong demand from the steel and construction markets (road and highway construction projects), before dropping to its lowest level in 2009 at approximately 2.5 percent below 1990 emissions, driven by the economic recession and downturn in major markets including construction, mining, and steel (USGS 2007, 2008,

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[12] The amount of CO_2 captured for sugar refining and PCC production is reported within the CRF tables under CRF Source Category 2H3, but within this report, they are included in this chapter.

2010). In 2010, the lime industry began to recover as the steel, FGD, and construction markets also recovered (USGS 2011 and 2012). Fluctuation in lime production since 2015 has been driven largely by demand from the steel making industry (USGS 2018b, 2019, 2020b, 2020c). In 2020, annual domestic lime production decreased due to temporary plant closures as a result of the COVID-19 pandemic (USGS 2021c).

Lime production in the United States—including Puerto Rico—was reported to be 15,862 kilotons in 2020, a decrease of about 6.1 percent compared to 2019 levels (USGS 2021b). Compared to 1990, lime production increased by about 0.1 percent. At year-end 2020, 74 primary lime plants were operating in the United States, including Puerto Rico according to the USGS MCS (USGS 2021a).[13] Principal lime producing states were Missouri, Alabama, Ohio, Texas, and Kentucky (USGS 2021a).

U.S. lime production resulted in estimated net CO_2 emissions of 11.3 MMT CO_2 Eq. (11,299 kt) (see Table 4-6 and Table 4-7). Carbon dioxide emissions from lime production decreased by about 6.7 percent compared to 2019 levels. Compared to 1990, CO_2 emissions have decreased by about 3.4 percent. The trends in CO_2 emissions from lime production are directly proportional to trends in production, which are described above.

Table 4-6: CO_2 Emissions from Lime Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	11.7	11,700
2005	14.6	14,552
2016	12.6	12,630
2017	12.9	12,882
2018	13.1	13,106
2019	12.1	12,112
2020	11.3	11,299

Table 4-7: Gross, Recovered, and Net CO_2 Emissions from Lime Production (kt)

Year	Gross	Recovered[a]	Net Emissions
1990	11,959	259	11,700
2005	15,074	522	14,552
2016	13,000	370	12,630
2017	13,283	401	12,882
2018	13,609	503	13,106
2019	12,676	564	12,112
2020	11,875	576	11,299

Note: Totals may not sum due to independent rounding.

[a] For sugar refining and PCC production.

Methodology and Time-Series Consistency

To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors using the Tier 2 approach from the *2006 IPCC Guidelines*. The emission factor is the product of the stoichiometric ratio between CO_2 and CaO, and the average CaO and MgO content for lime. The

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[13] In 2020, 71 operating primary lime facilities in the United States reported to the EPA Greenhouse Gas Reporting Program, including three facilities that reported emission values of zero.

CaO and MgO content for lime is assumed to be 95 percent for both high-calcium and dolomitic lime (IPCC 2006). The emission factors were calculated as follows:

Equation 4-2: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, High-Calcium Lime (Equation 2.9)

$$EF_{\text{High-Calcium Lime}} = [(44.01 \text{ g/mole } CO_2) \div (56.08 \text{ g/mole CaO})] \times (0.9500 \text{ CaO/lime}) = 0.7455 \text{ g } CO_2\text{/g lime}$$

Equation 4-3: *2006 IPCC Guidelines* Tier 2 Emission Factor for Lime Production, Dolomitic Lime (Equation 2.9)

$$EF_{\text{Dolomitic Lime}} = [(88.02 \text{ g/mole } CO_2) \div (96.39 \text{ g/mole CaO})] \times (0.9500 \text{ CaO/lime}) = 0.8675 \text{ g } CO_2\text{/g lime}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H_2O to ($Ca(OH)_2$ and [$Ca(OH)_2 \bullet Mg(OH)_2$]) (IPCC 2006). These factors set the chemically combined water content to 27 percent for high-calcium hydrated lime, and 30 percent for dolomitic hydrated lime.

The *2006 IPCC Guidelines* (Tier 2 method) also recommends accounting for emissions from lime kiln dust (LKD) through application of a correction factor. LKD is a byproduct of the lime manufacturing process typically not recycled back to kilns. LKD is a very fine-grained material and is especially useful for applications requiring very small particle size. Most common LKD applications include soil reclamation and agriculture. Emissions from the application of lime for agricultural purposes are reported in the Agriculture chapter under 5.5 Liming (CRF Source Category 3G). Currently, data on annual LKD production is not readily available to develop a country-specific correction factor. Lime emission estimates were multiplied by a factor of 1.02 to account for emissions from LKD (IPCC 2006). See the Planned Improvements section associated with efforts to improve uncertainty analysis and emission estimates associated with LKD.

Lime emission estimates were further adjusted to account for the amount of CO_2 captured for use in on-site processes. All the domestic lime facilities are required to report these data to EPA under its GHGRP. The total national-level annual amount of CO_2 captured for on-site process use was obtained from EPA's GHGRP (EPA 2021) based on reported facility-level data for years 2010 through 2020. The amount of CO_2 captured/recovered for on-site process use is deducted from the total gross emissions (i.e., from lime production and LKD). The net lime emissions are presented in Table 4-6 and Table 4-7. GHGRP data on CO_2 removals (i.e., CO_2 captured/recovered) was available only for 2010 through 2020. Since GHGRP data are not available for 1990 through 2009, IPCC "splicing" techniques were used as per the *2006 IPCC Guidelines* on time-series consistency (IPCC 2006, Volume 1, Chapter 5).

Lime production data by type (i.e., high-calcium and dolomitic quicklime, high-calcium and dolomitic hydrated lime, and dead-burned dolomite) for 1990 through 2020 (see Table 4-8) were obtained from U.S. Geological Survey (USGS) Minerals Yearbook (USGS 1992 through 2021b) and are compiled by USGS to the nearest ton. Dead-burned dolomite data are additionally rounded by USGS to no more than one significant digit to avoid disclosing company proprietary data. Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not manufactured in the United States (USGS 2018a). Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent based on recommendations from the IPCC and using the water content values for high-calcium hydrated lime and dolomitic hydrated lime mentioned above, and is presented in Table 4-9 (IPCC 2006). The CaO and CaO•MgO contents of lime, both 95 percent, were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) were not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three-year distribution from 1997 to 1999.

Table 4-8: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (kt)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
2005	14,100	2,990	2,220	474	200
2016	12,100	2,420	2,350	280	200
2017	12,200	2,650	2,360	276	200
2018	12,400	2,810	2,430	265	200
2019	11,300	2,700	2,430	267	200
2020	10,700	2,390	2,320	252	200

Table 4-9: Adjusted Lime Production (kt)

Year	High-Calcium	Dolomitic
1990	12,466	2,800
2005	15,721	3,522
2016	13,816	2,816
2017	13,923	3,043
2018	14,174	3,196
2019	13,074	3,087
2020	12,394	2,766

Note: Minus water content of hydrated lime.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of lime products and CO_2 recovery rates for on-site process use over the time series. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants produce lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed, especially at captive lime production facilities. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). Carbon dioxide reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2, whereas most of the lime used in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. Quantifying the amount of CO_2 that is reabsorbed would require a detailed accounting of lime use in the United States and additional information about the associated processes where both the lime and byproduct CO_2 are "reused." Research conducted thus far has not yielded the necessary information to quantify CO_2

reabsorption rates.[14] Some additional information on the amount of CO_2 consumed on site at lime facilities, however, has been obtained from EPA's GHGRP.

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[15] The lime generated by these processes is included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic carbon (C) is present from the wood. Kraft mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime manufacturing process, the CO_2 emitted during this process is mostly biogenic in origin and therefore is not included in the industrial processes totals (Miner and Upton 2002). In accordance with IPCC methodological guidelines, any such emissions are calculated by accounting for net C fluxes from changes in biogenic C reservoirs in wooded or crop lands (see the Land Use, Land-Use Change, and Forestry chapter).

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

Another uncertainty is the assumption that calcination emissions for LKD are around 2 percent. The National Lime Association (NLA) has commented that the estimates of emissions from LKD in the United States could be closer to 6 percent. They also note that additional emissions (approximately 2 percent) may also be generated through production of other byproducts/wastes (off-spec lime that is not recycled, scrubber sludge) at lime plants (Seeger 2013). Publicly available data on LKD generation rates, total quantities not used in cement production, and types of other byproducts/wastes produced at lime facilities are limited. NLA compiled and shared historical emissions information and quantities for some waste products reported by member facilities associated with generation of total calcined byproducts and LKD, as well as methodology and calculation worksheets that member facilities complete when reporting. There is uncertainty regarding the availability of data across the time series needed to generate a representative country-specific LKD factor. Uncertainty of the activity data is also a function of the reliability and completeness of voluntarily reported plant-level production data. Further research, including outreach and discussion with NLA, and data is needed to improve understanding of additional calcination emissions to consider revising the current assumptions that are based on IPCC guidelines. More information can be found in the Planned Improvements section below.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-10. Lime CO_2 emissions for 2020 were estimated to be between 11.1 and 11.5 MMT CO_2 Eq. at the 95 percent confidence level. This confidence level indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 11.3 MMT CO_2 Eq.

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[14] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[15] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2$ + heat $\rightarrow CaO + H_2O$], and no CO_2 is released.

Table 4-10: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	11.3	11.1	11.5	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as noted in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods associated with reporting on CO_2 captured for onsite use applicable to lime manufacturing facilities can be found under Subpart S (Lime Manufacturing) of the GHGRP regulation (40 CFR Part 98).[16] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2020).[17] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

EPA plans to review GHGRP emissions and activity data reported to EPA under Subpart S of the GHGRP regulation (40 CFR Part 98), and aggregated activity data on lime production by type in particular. In addition, initial review of data has identified that several facilities use CEMS to report emissions. Under Subpart S, if a facility is using a CEMS, they are required to report combined combustion emissions and process emissions. EPA continues to review how best to incorporate GHGRP and notes that particular attention will be made to also ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required because the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[18]

Future improvements involve improving and/or confirming the representativeness of current assumptions associated with emissions from production of LKD and other byproducts/wastes as discussed in the Uncertainty section, per comments from the NLA provided during a prior Public Review comment period for a previous Inventory (i.e., 1990 through 2018) . EPA met with NLA in summer of 2020 for clarification on data needs and

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[16] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[17] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[18] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

available data and to discuss planned research into GHGRP data. Previously, EPA met with NLA in spring of 2015 to outline specific information required to apply IPCC methods to develop a country-specific correction factor to more accurately estimate emissions from production of LKD. In 2016, NLA compiled and shared historical emissions information reported by member facilities on an annual basis under voluntary reporting initiatives from 2002 through 2011 associated with generation of total calcined byproducts and LKD. Reporting of LKD was only differentiated for the years 2010 and 2011. This emissions information was reported on a voluntary basis consistent with NLA's facility-level reporting protocol, which was also provided to EPA. To reflect information provided by NLA, EPA updated the qualitative description of uncertainty. At the time of this Inventory, this planned improvement is in process and has not been incorporated into this current Inventory report.

4.3 Glass Production (CRF Source Category 2A3)

Glass production is an energy and raw-material intensive process that results in the generation of carbon dioxide (CO_2) from both the energy consumed in making glass and the glass production process itself. Emissions from fuels consumed for energy purposes during the production of glass are included in the Energy sector.

Glass production employs a variety of raw materials in a glass-batch. These include formers, fluxes, stabilizers, and sometimes colorants. The major raw materials (i.e., fluxes and stabilizers) that emit process-related CO_2 emissions during the glass melting process are limestone, dolomite, and soda ash. The main former in all types of glass is silica (SiO_2). Other major formers in glass include feldspar and boric acid (i.e., borax). Fluxes are added to lower the temperature at which the batch melts. Most commonly used flux materials are soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2O). Stabilizers make glass more chemically stable and keep the finished glass from dissolving and/or falling apart. Commonly used stabilizing agents in glass production are limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$), alumina (Al_2O_3), magnesia (MgO), barium carbonate ($BaCO_3$), strontium carbonate ($SrCO_3$), lithium carbonate (Li_2CO_3), and zirconia (ZrO_2) (DOE 2002). Glass makers also use a certain amount of recycled scrap glass (cullet), which comes from in-house return of glassware broken in the production process or other glass spillage or retention, such as recycling or from cullet broker services.

The raw materials (primarily soda ash, limestone, and dolomite) release CO_2 emissions in a complex high-temperature chemical reaction during the glass melting process. This process is not directly comparable to the calcination process used in lime manufacturing, cement manufacturing, and process uses of carbonates (i.e., limestone/dolomite use) but has the same net effect in terms of CO_2 emissions (IPCC 2006).

The U.S. glass industry can be divided into four main categories: containers, flat (window) glass, fiber glass, and specialty glass. The majority of commercial glass produced is container and flat glass (EPA 2009). The United States is one of the major global exporters of glass. Domestically, demand comes mainly from the construction, auto, bottling, and container industries. There are more than 1,700 facilities that manufacture glass in the United States, with the largest companies being Corning, Guardian Industries, Owens-Illinois, and PPG Industries.[19]

The glass container sector is one of the leading soda ash consuming sectors in the United States. In 2020, glass production accounted for 48 percent of total domestic soda ash consumption (USGS 2021). Emissions from soda ash production are reported in 4.12 Soda Ash Production (CRF Source Category 2B7).

In 2020, 2,130 kilotons of soda ash, 1,334 kilotons of limestone, and 824 kilotons of dolomite were consumed for glass production (USGS 2021; EPA 2021). Use of soda ash, limestone, and dolomite in glass production resulted in aggregate CO_2 emissions of 1.9 MMT CO_2 Eq. (1,857 kt) (see Table 4-11). Overall, emissions have decreased by 19

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[19] Excerpt from Glass & Glass Product Manufacturing Industry Profile, First Research. Available online at: http://www.firstresearch.com/Industry-Research/Glass-and-Glass-Product-Manufacturing.html.

percent compared to 1990. Glass production and emissions decreased by about 4 percent compared to 2019 levels.

Emissions from glass production have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. Specifically, the extended downturn in residential and commercial construction and automotive industries between 2008 and 2010 resulted in reduced consumption of glass products, causing a drop in global demand for limestone/dolomite and soda ash and resulting in lower emissions. Some commercial food and beverage package manufacturers are shifting from glass containers towards lighter and more cost-effective polyethylene terephthalate (PET) based containers, putting downward pressure on domestic consumption of soda ash (USGS 1995 through 2015b). Due to the COVID-19 pandemic, glass production dropped in the spring of 2020 but mostly rebounded by the end of the year (Federal Reserve 2021).

Table 4-11: CO_2 Emissions from Glass Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	2.3	2,291
2005	2.4	2,432
2016	2.1	2,119
2017	2.0	2,011
2018	2.0	1,989
2019	1.9	1,938
2020	1.9	1,857

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 3 method by multiplying the quantity of input carbonates (limestone, dolomite, and soda ash) by the IPCC default carbonate-based emission factor (in metric tons CO_2/metric ton carbonate).

The methodology for estimating CO_2 emissions from the use of soda ash for glass production remains unchanged for 1990 to 2020. This methodology continues to assume that soda ash contains 100 percent sodium carbonate (Na_2CO_3), consistent with *2006 IPCC Guidelines* and the previous methodology. For 1990 through 2020, data on soda ash used for glass manufacturing were obtained from the U.S. Bureau of Mines (1991 and 1993a), the *USGS Minerals Yearbook: Soda Ash Annual Report* (USGS 1995 through 2015b), and *USGS Mineral Industry Surveys for Soda Ash* (USGS 2017 through 2021).

2010 through 2020

For this Inventory, the methodology for estimating CO_2 emissions from the use of limestone and dolomite for glass production for years 2010 through 2020 has changed to use new activity data reported to the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) on the quantities of limestone and dolomite used for glass production (EPA 2021). USGS data on the quantity of soda ash used for glass production continues to be used because it was obtained directly from the soda ash producers and includes use by smaller artisanal glass operations, which are excluded in the GHGRP data.

GHGRP collects data from glass production facilities with greenhouse gas emissions greater than 25,000 metric tons CO_2 Eq. The reporting threshold is used to exclude artisanal glass operations that are expected to have much lower greenhouse gas emissions than the threshold. These smaller facilities have not been accounted for yet for this portion of the time series due to limited data. Facilities report the total quantity of each type of carbonate (e.g., limestone, dolomite, soda ash) used in glass production each year to GHGRP, with data collection starting in 2010 (EPA 2021).

Using the total quantities of each carbonate, EPA calculated the metric tons of emissions resulting from glass production by multiplying the quantity of input carbonates (i.e., limestone, dolomite, and soda ash) by IPCC default carbonate-based emission factors (in metric tons CO_2/metric ton carbonate): limestone, 0.43971; dolomite, 0.47732; and soda ash, 0.41492 and by the average carbonate-based mineral mass fraction for each year. The average carbonate-based mineral mass fractions from the GHGRP, averaged across 2010 through 2020, indicate that the limestone used in glass production contained 98.6 percent calcium carbonate ($CaCO_3$) and dolomite contained 98.5 percent calcium magnesium carbonate ($CaMg(CO_3)_2$). The previous methodology assumed that limestone contained 100 percent $CaCO_3$ and dolomite contained 100 percent $CaMg(CO_3)_2$. This methodology continues to assume that soda ash contains 100 percent sodium carbonate (Na_2CO_3), consistent with *2006 IPCC Guidelines* and the previous methodology.

1990 through 2009

Data from GHGRP on the quantity of limestone and dolomite used in glass production is not available for 1990 through 2009. USGS and GHGRP datasets for 2010 through 2020 showed inconsistent overlap, and using USGS data for 1990 through 2009 would have introduced inconsistencies over the time series.

To address time-series consistency, total emissions from 1990 to 2009 were calculated using the Federal Reserve Industrial Production Index for glass production in the United States as a surrogate for the total quantity of carbonates used in glass production. The production index measures real output expressed as a percentage of real output in a base year, which is currently 2017 (Federal Reserve 2021). Since January 1971, the Federal Reserve has released the monthly glass production index for NAICS code 3272 (Glass and Glass Product Manufacturing) as part of release G.17, "Industrial Production and Capacity Utilization" (Federal Reserve 2021). The monthly index values for each year were averaged to calculate an average annual glass production index value. Total annual emissions were calculated by taking a ratio of the average annual glass production index for each year, with a base year of 2017, and the calculated 2017 emissions based on GHGRP data.

Emissions from limestone and dolomite consumption were disaggregated from total annual emissions, using the average percent contribution of each carbonate to total annual emissions for 2010 through 2020 based on GHGRP data: 32.1 percent limestone and 19.0 percent dolomite. A comparison of the 1990 to 2009 methodology applied to 2010 to 2020 and the calculated emissions based on GHGRP data of quantities of carbonates consumed for glass production for 2010 to 2020 showed that these two methods are closely correlated. The methodology for estimating CO_2 emissions from the use of soda ash for glass production and data sources for the amount of soda ash used in glass production are described above.

The amount of limestone, dolomite, and soda ash used in glass production each year and the annual average Federal Reserve production indices for glass production are shown in Table 4-12.

Table 4-12: Limestone, Dolomite, and Soda Ash Used in Glass Production (kt) and Average Annual Production Index for Glass and Glass Product Manufacturing

Activity	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Limestone	1,391	1,668	1,560	1,488	1,442	1,370	1,334
Dolomite	757	908	836	806	871	883	824
Soda Ash	3,177	3,050	2,510	2,360	2,280	2,220	2,130
Total	**5,325**	**5,626**	**4,906**	**4,653**	**4,593**	**4,473**	**4,287**
Production Index[a]	94.3	113.1	102.6	100	102.5	100	91.1

[a] Average Annual Production Index uses 2017 as the base year.

Note: Totals may not sum due to independent rounding.

As discussed above, methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare USGS and GHGRP data sets for 2010 through 2020. To address the inconsistencies, adjustments were made as described above.

Uncertainty

The methodology and activity data used in this Inventory reduced uncertainty for glass production, compared to the previous Inventory. Uncertainty levels presented in this section in previous Inventories arose in part due to variations in the chemical composition of limestone used in glass production. For example in addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals (e.g., potassium carbonate, strontium carbonate and barium carbonate, and dead burned dolomite). The methodology in this Inventory report uses GHGRP data on the average mass fraction of each mineral in the limestone and dolomite used in glass production for each year from 2010-2020.

The data and methodology used in this Inventory report also reduce uncertainty associated with activity data. The methodology uses the amount of limestone and dolomite used in glass manufacturing which is reported directly by the glass manufacturers for years 2010 through 2020 and the amount of soda ash used in glass manufacturing which is reported by soda ash producers for the full time series. The emissions from other carbonates reported to GHGRP–barium carbonate ($BaCO_3$), potassium carbonate (K_2CO_3), lithium carbonate (Li_2CO_3), and strontium carbonate ($SrCO_3$)–are not included in these estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-13. In 2020, glass production CO_2 emissions were estimated to be between 1.8 and 1.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below and 2 percent above the emission estimate of 1.9 MMT CO_2 Eq.

Table 4-13: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Glass Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Glass Production	CO_2	1.9	1.8	1.9	-2%	+2%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[20] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

For the current Inventory, a new methodology using more complete activity data from GHGRP for 2010 through 2020 and the industrial production index for glass and glass product manufacturing from the Federal Reserve for

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[20] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

1990 through 2009 to address time-series consistency were implemented and is described under the Methodology and Time-Series Consistency section. The revised values for 1990 through 2019 resulted in increased emissions estimates for all years. Across the time series, emissions increased by an average of 52 percent compared to the previous Inventory. Annual emission increases during the time series ranged from an 18 percent increase in 2006 (373 kt) to a 91 percent increase in 1999 (1,238 kt).

Planned Improvements

EPA incorporated data from GHGRP on limestone and dolomite used for glass production into the emissions estimates for the Glass Production source category for 1990 through 2020. EPA continues to evaluate and analyze data reported under GHGRP that would be useful to improve the emission estimates for the Glass Production source category, particularly the use of barium carbonate, potassium carbonate, lithium carbonate, and strontium carbonate for glass production. EPA will also evaluate updates to uncertainty levels for the activity data and mineral mass fraction values from EPA's GHGRP. This is a near-term planned improvement.

Some glass producing facilities in the United States do not report to EPA's GHGRP because they fall below the reporting threshold for this industry. EPA will continue ongoing research on the availability of data to better assess the completeness of emission estimates from glass production and assess how to refine the methodology to ensure complete national coverage of this category. Research will include reassessing previous assessments of GHGRP industry coverage using the reporting threshold of 25,000 metric tons CO_2 Eq. This is a medium-term planned improvement.

4.4 Other Process Uses of Carbonates (CRF Source Category 2A4)

Limestone ($CaCO_3$), dolomite ($CaCO_3MgCO_3$),[21] and other carbonates such as soda ash, magnesite, and siderite are basic materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control. This section addresses only limestone, dolomite, and soda ash use. For industrial applications, carbonates such as limestone and dolomite are heated sufficiently enough to calcine the material and generate CO_2 as a byproduct.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$MgCO_3 \rightarrow MgO + CO_2$$

Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization (FGD) systems for utility and industrial plants, and as a raw material for the production of glass, lime, and cement. Emissions from limestone and dolomite used in the production of cement, lime, glass, and iron and steel are excluded from the Other Process Uses of Carbonates category and reported under their respective source categories (e.g., Section 4.2, Glass Production). Emissions from soda ash production are reported under Section 4.12 Soda Ash Production (CRF Source Category 2B7). Emissions from soda ash consumption associated with glass manufacturing are reported under Section 4.2 Glass Production (CRF Source Category 2A3). Emissions from the use of limestone and dolomite in liming of agricultural soils are included in the Agriculture chapter under Liming (CRF Source Category 3G). Emissions from fuels consumed for energy purposes during these processes are accounted for in the Energy chapter under Section 3.1 Fossil Fuel Combustion (CRF Source Category 1A). Both lime (CaO) and limestone ($CaCO_3$) can be used as a sorbent for FGD systems. Emissions from lime consumption for FGD systems and from sugar refining are reported under Section 4.3 Lime Production (CRF Source Category 2A2).

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[21] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Emissions from the use of dolomite in primary magnesium metal production are reported under Section 4.20 Magnesium Production and Processing (CRF Source Category 2C4).

Limestone and dolomite are widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. In 2017, the leading limestone producing states were Texas, Florida, Missouri, Ohio, and Pennsylvania, which contributed 44 percent of the total U.S. output (USGS 2021a). Dolomite deposits are found in the United States, Canada, Mexico, Europe, Africa, and Brazil. In the United States, the leading dolomite producing states are Pennsylvania, New York, and Utah which currently contribute more than a third of the total U.S. output (USGS 2021a). Internationally, two types of soda ash are produced: natural and synthetic. In 2019, 93 percent of the global soda ash production came from China, the United States, Russia, Germany, India, Turkey, Poland, and France. The United States only produces natural soda ash and only in two states: Wyoming and California (USGS 2021c).

In 2020, 15,346 kilotons (kt) of limestone, 4,374 kt of dolomite, and 2,310 kt of soda ash were consumed for these emissive applications, which excludes consumption for the production of cement, lime, glass, and iron and steel (Willett 2021, USGS 2021d). Limestone and dolomite consumption data for 2020 were not available in time for publication and were estimated using 2019 values, as described in the Methodology and Time-Series Consistency section below. Usage of limestone, dolomite and soda ash resulted in aggregate CO_2 emissions of 9.8 MMT CO_2 Eq. (9,794 kt) (see Table 4-14 and Table 4-15). The 2019 and 2020 emissions increased over 30 percent compared to 2018, primarily as a result of increased limestone consumption attributed to sulfur oxide removal usage for FGD systems and dolomite consumption attributed to flux stone. Disruptions in the mining and construction industries associated with the COVID-19 pandemic led to decreased consumption of crushed stone in 2020; however, the impacts on emissions from limestone and dolomite consumption are not able to be quantified without more detailed information on consumption from the emissive sources in 2020 (USGS 2021b). Overall emissions have increased 57 percent from 1990 through 2020.

Table 4-14: CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq.)

Year	Flux Stone	FGD	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2.6	1.4	1.4	0.8	**6.2**
2005	2.6	3.0	1.3	0.5	**7.5**
2016	2.6	6.2	1.1	1.0	**10.8**
2017	2.4	5.6	1.1	0.8	**9.9**
2018	2.8	2.2	1.1	1.3	**7.4**
2019	4.8	3.5	1.0	0.5	**9.8**
2020	4.8	3.5	1.0	0.5	**9.8**

[a] Soda ash consumption not associated with glass manufacturing.

[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, and acid neutralization.

Note: Totals may not sum due to independent rounding.

Table 4-15: CO_2 Emissions from Other Process Uses of Carbonates (kt)

Year	Flux Stone	FGD	Soda Ash Consumption[a]	Other Miscellaneous Uses[b]	Total
1990	2,592	1,432	1,390	819	**6,233**
2005	2,649	2,973	1,305	533	**7,459**
2016	2,585	6,164	1,082	981	**10,813**
2017	2,441	5,598	1,058	771	**9,869**
2018	2,795	2,229	1,069	1,259	**7,351**
2019	4,811	3,537	1,036	463	**9,848**
2020	4,835	3,537	958	463	**9,794**

[a] Soda ash consumption not associated with glass manufacturing.

[b] "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, and acid neutralization.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Carbon dioxide emissions were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the quantity of limestone or dolomite consumed by the emission factor for limestone or dolomite calcination, respectively: 0.43971 metric ton CO_2/metric ton carbonate for limestone and 0.47732 metric ton CO_2/metric ton carbonate for dolomite.[22] This methodology was used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization. Flux stone used during the production of iron and steel was deducted from the Other Process Uses of Carbonates source category estimate and attributed to the Iron and Steel Production source category estimate. Similarly, limestone and dolomite consumption for glass manufacturing, cement, and lime manufacturing are excluded from this category and attributed to their respective categories.

Consumption data for 1990 through 2019 of limestone and dolomite used for flux stone, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, and acid neutralization (see Table 4-16) were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Crushed Stone Annual Report* (1995a through 2017, 2020a, 2020c), preliminary data for 2019 from USGS Crushed Stone Commodity Expert (Willett 2021), American Iron and Steel Institute limestone and dolomite consumption data (AISI 2018 through 2020), and the U.S. Bureau of Mines (1991 and 1993a), which are reported to the nearest ton. Limestone and dolomite consumption data for 2020 were not available at the time of publication and were estimated using 2019 values. In addition, the estimated values for limestone and dolomite consumption for flux stone used during the production of iron and steel were adjusted down, using emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to account for the impacts of the COVID-19 pandemic in 2020. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020 (EPA 2021). This adjustment method is consistent with the method used in Section 4.17 (CRF Source Category 2C1) and Metallurgical Coke Production. Similar data on 2020 emissions trends were not available for the other process uses included in this section, which prevented the use of a similar approach.

During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use; therefore, data on consumption by end use for 1990 was estimated by applying the 1991 ratios of total limestone and dolomite consumption by end use to total 1990 limestone and dolomite consumption values. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 ratios of total limestone and dolomite use by end uses to the 1992 total values.

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[22] *2006 IPCC Guidelines*, Volume 3: Chapter 2, Table 2.1.

In 1991, the U.S. Bureau of Mines, now known as the USGS, began compiling production and end use information through surveys of crushed stone manufacturers. Manufacturers provided different levels of detail in survey responses, so information was divided into three categories: (1) production by end-use, as reported by manufacturers (i.e., "specified" production); (2) production reported by manufacturers without end-uses specified (i.e., "unspecified-reported" production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., "unspecified-estimated" production). Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses; (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years; or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

A large quantity of crushed stone was reported to the USGS under the category "unspecified uses." A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to all other reported end-uses according to each end-use's fraction of total consumption in that year.[23]

Table 4-16: Limestone and Dolomite Consumption (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Flux Stone	5,842	5,745	5,686	5,447	6,242	10,570	10,622
Limestone	*5,237*	*2,492*	*3,415*	*4,216*	*4,891*	*6,222*	*6,248*
Dolomite	*605*	*3,254*	*2,270*	*1,230*	*1,351*	*4,348*	*4,374*
FGD	3,258	6,761	14,019	12,732	5,068	8,045	8,045
Other Miscellaneous Uses	1,835	1,212	2,231	1,754	2,862	1,054	1,054
Total	**10,935**	**13,719**	**21,935**	**19,932**	**14,172**	**19,668**	**19,720**

Note: Totals may not sum due to independent rounding.

Excluding glass manufacturing which is reported under Section 4.2 Glass Production (CRF Source Category 2A3), most soda ash is consumed in chemical production, with minor amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment. As soda ash is consumed for these purposes, CO_2 is usually emitted. In these applications, it is assumed that one mole of carbon is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of carbon (or 0.415 metric tons of CO_2) are released for every metric ton of soda ash consumed. The activity data for soda ash consumption for 1990 to 2020 (see Table 4-17) were obtained from the U.S. Geological Survey (USGS) Minerals Yearbook for Soda Ash (1994 through 2015b) and USGS Mineral Industry Surveys for Soda Ash (USGS 2017a, 2018, 2019, 2020b, 2021d). Soda ash consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Table 4-17: Soda Ash Consumption Not Associated with Glass Manufacturing (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Soda Ash[a]	3,351	3,144	2,608	2,550	2,576	2,497	2,310

[a] Soda ash consumption is sales reported by producers which exclude imports. Historically, imported soda ash is less than 1 percent of the total U.S. consumption (Kostick 2012).

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

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[23] This approach was recommended by USGS, the data collection agency.

Uncertainty

The uncertainty levels presented in this section account for uncertainty associated with activity data. Data on limestone and dolomite consumption are collected by USGS through voluntary national surveys. USGS contacts the mines (i.e., producers of various types of crushed stone) for annual sales data. Data on other carbonate consumption are not readily available. The producers report the annual quantity sold to various end-users and industry types. USGS estimates the historical response rate for the crushed stone survey to be approximately 70 percent, and the rest is estimated by USGS. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the producer/mines and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. Lastly, much of the limestone consumed in the United States is reported as “other unspecified uses;” therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses. EPA contacted the USGS National Minerals Information Center Crushed Stone commodity expert to assess the current uncertainty ranges associated with the limestone and dolomite consumption data compiled and published by USGS. During this discussion, the expert confirmed that EPA’s range of uncertainty was still reasonable (Willett 2017).

Uncertainty in the estimates also arises in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed.

For emissions from soda ash consumption, the primary source of uncertainty results from the fact that these emissions are dependent upon the type of processing employed by each end-use. Specific emission factors for each end-use are not available, so a Tier 1 default emission factor is used for all end-uses. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash. Additional uncertainty comes from the reported consumption and allocation of consumption within sectors that is collected on a quarterly basis by the USGS. Efforts have been made to categorize company sales within the correct end-use sector.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-18. Carbon dioxide emissions from other process uses of carbonates in 2020 were estimated to be between 8.2 and 12.9 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 28 percent above the emission estimate of 9.8 MMT CO_2 Eq.

Table 4-18: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Other Process Uses of Carbonates (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Other Process Uses of Carbonates	CO_2	9.8	8.2	12.9	-19%	+28%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Emissions from carbonate consumption for magnesium metal production previously included in this chapter have been moved from Other Process Uses of Carbonates to Section 4.20 Magnesium Production and Processing (CRF Source Category 2C4) in the current Inventory, consistent with the *2006 IPCC Guidelines*. Emissions were removed from this chapter for 1990 through 2001, resulting in approximately 50 to 70 kt CO_2 reduction for these years.

Emissions previously included in this chapter for limestone consumption for sugar refining have been removed in the current inventory, as it was determined that these emissions are already accounted for in the Lime Production source category emissions. Emissions were removed from this chapter for 1990 through 2019, resulting in a range of 0 to 1,500 kt CO_2 reduction for these years.

Additionally, for the current Inventory, updated USGS data on limestone and dolomite consumption was available for 2019, resulting in updated emissions estimates for that year. Compared to the previous Inventory, emissions for 2019 increased by 32 percent (2,391 kt CO_2 Eq.).

Planned Improvements

In response to comments received during previous Inventory reports from the UNFCCC, EPA has inquired to the availability of ceramics and non-metallurgical magnesia data. The USGS notes that this data is not currently reported by survey respondents. EPA continues to conduct outreach with other entities, but at this time, the research has not yielded any alternative data on national levels of carbonates. This improvement remains ongoing, and EPA plans to continue to update this Planned Improvements section in future reports as more information becomes available.

EPA also plans to continue dialogue with USGS to assess uncertainty ranges for activity data used to estimate emissions from other process use of carbonates. This planned improvement is currently planned as a medium-term improvement.

4.5 Ammonia Production (CRF Source Category 2B1)

Emissions of carbon dioxide (CO_2) occur during the production of synthetic ammonia (NH_3), primarily through the use of natural gas, petroleum coke, or naphtha as a feedstock. The natural gas-, naphtha-, and petroleum coke-based processes produce CO_2 and hydrogen (H_2), the latter of which is used in the production of ammonia. The brine electrolysis process for production of ammonia does not lead to process-based CO_2 emissions. Due to national circumstances, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. More information on this approach can be found in the Methodology section below.

Ammonia production requires a source of nitrogen (N) and hydrogen (H). Nitrogen is obtained from air through liquid air distillation or an oxidative process where air is burnt and the residual nitrogen is recovered. In the United States, the majority of ammonia is produced using a natural gas feedstock as the hydrogen source. One synthetic ammonia production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some U.S. plants, some of the CO_2 produced by the process is captured and used to produce urea rather than being emitted to the atmosphere. In 2020, 16 companies operated 35 ammonia producing facilities in 16 states. Approximately 60 percent of domestic ammonia production capacity is concentrated in Louisiana, Oklahoma, and Texas (USGS 2021).

Synthetic ammonia production from natural gas feedstock consists of five principal process steps. The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 percent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. In the shift conversion step, the CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air. Carbon dioxide is removed from the process gas by the shift conversion process, and the H_2 is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released from the solution.

The conversion process for conventional steam reforming of CH_4, including the primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88CH_4 + 1.26Air + 1.24H_2O \rightarrow 0.88CO_2 + N_2 + 3H_2$$

$$N_2 + 3H_2 \rightarrow 2NH_3$$

To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO_2 and H_2. These gases are separated, and the H_2 is used as a feedstock to the ammonia production process, where it is reacted with N_2 to form ammonia.

Not all of the CO_2 produced during the production of ammonia is emitted directly to the atmosphere. Some of the ammonia and some of the CO_2 produced by the synthetic ammonia process are used as raw materials in the production of urea [$CO(NH_2)_2$], which has a variety of agricultural and industrial applications.

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Only the CO_2 emitted directly to the atmosphere from the synthetic ammonia production process is accounted for in determining emissions from ammonia production. The CO_2 that is captured during the ammonia production process and used to produce urea does not contribute to the CO_2 emission estimates for ammonia production presented in this section. Instead, CO_2 emissions resulting from the consumption of urea are attributed to the urea consumption or urea application source category (under the assumption that the carbon stored in the urea during its manufacture is released into the environment during its consumption or application). Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 Urea Fertilization (CRF Source Category 3H) of the Agriculture chapter. Emissions of CO_2 resulting from non-agricultural applications of urea (e.g., use as a feedstock in chemical production processes) are accounted for in Section 4.5 Urea Consumption for Non-Agricultural Purposes of this chapter.

Total emissions of CO_2 from ammonia production in 2020 were 12.7 MMT CO_2 Eq. (12,717 kt) and are summarized in Table 4-19 and Table 4-20. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, market fluctuations and volatility in natural gas prices affect the production of ammonia. Since 1990, emissions from ammonia production have decreased by about 3 percent. Emissions in 2020 increased by about 4 percent from the 2019 levels.

Emissions from ammonia production have increased steadily since 2016, due to the addition of new ammonia production facilities and new production units at existing facilities in 2016, 2017, and 2018. Agriculture continues to drive demand for nitrogen fertilizers, comprising of approximately 88 percent of domestic ammonia consumption. In 2020 during the COVID-19 pandemic, the fertilizer industry was considered part of the critical chemical sector by the U.S. Department of Homeland Security. The COVID-19 pandemic stay-at-home orders issued in March 2020 did not affect the fertilizer industry, and U.S. ammonia plants maintained full operations (USGS 2021).

Table 4-19: CO_2 Emissions from Ammonia Production (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Ammonia Production	13.0	9.2	10.2	11.1	12.2	12.3	12.7

Table 4-20: CO_2 Emissions from Ammonia Production (kt)

Source	1990	2005	2016	2017	2018	2019	2020
Ammonia Production	13,047	9,177	10,245	11,112	12,163	12,272	12,717

Methodology and Time-Series Consistency

For this Inventory, CO_2 emissions from the production of synthetic ammonia from natural gas feedstock are estimated using a country-specific approach modified from the *2006 IPCC Guidelines* (IPCC 2006) Tier 1 and 2 methods. In the country-specific approach, emissions are not based on total fuel requirement per the *2006 IPCC Guidelines* due to data disaggregation limitations of energy statistics provided by the Energy Information Administration (EIA). Data on total fuel use (including fuel used for ammonia feedstock and fuel used for energy) for ammonia production are not known in the United States. EIA does not provide data broken out by industrial category, only at the broad industry sector level. To estimate emissions, a country-specific emission factor is developed and applied to national ammonia production to estimate ammonia-production emissions from feedstock fuel use. Emissions from fuel used for energy at ammonia plants are included in the overall EIA Industrial sector energy use and accounted for in the Energy chapter.

The country-specific approach uses a CO_2 emission factor of 1.2 metric tons CO_2/metric ton NH_3, which is published by the European Fertilizer Manufacturers Association (EFMA) and is based on natural gas-based ammonia production technologies that are similar to those employed in the United States (EFMA 2000a). The EFMA reported an emission factor range of 1.15 to 1.30 metric tons CO_2 per metric ton NH_3, with 1.2 metric tons CO_2 per metric ton NH_3 as a typical value (EFMA 2000a). Technologies (e.g., catalytic reforming process, etc.) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. This country-specific approach is compatible with the *2006 IPCC Guidelines* as it is based on the same scientific approach that the carbon in the fuel used to produce ammonia is released as CO_2. The CO_2 emission factor is applied to the percent of total annual domestic ammonia production from natural gas feedstock.

Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. The CO_2 emissions reported for ammonia production are reduced by a factor of 0.733 multiplied by total annual domestic urea production. This corresponds to a stoichiometric CO_2/urea factor of 44/60, assuming complete conversion of ammonia (NH_3) and CO_2 to urea (IPCC 2006; EFMA 2000b).

All synthetic ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at one plant located in Kansas. Annual ammonia and urea production are shown in Table 4-21.

The implied CO_2 emission factor for total ammonia production is a combination of the emission factors for ammonia production from natural gas and from petroleum coke. Changes in the relative production of ammonia from natural gas and petroleum coke will impact overall emissions and emissions per ton of total ammonia produced. For example, between 2000 and 2001 there were increases in the amount of ammonia produced from petroleum coke which caused increases in the implied emission factor across those years.

The CO_2 emission factor for petroleum coke feedstock is 3.52 metric tons of CO_2 per metric ton of NH_3 and is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock. The CO_2 emission factor is based on an average of the ratio of ammonia production from petroleum coke for years 2010 through 2015 (ACC 2020) and the facility-specific CO_2 emissions from the one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock for years 2010 through 2015 (EPA 2021b). Ammonia and urea are assumed to be manufactured in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process.

The methodology for ammonia produced from petroleum coke shifts in 2016 when the parent company of the facility manufacturing ammonia from petroleum coke feedstock, CVR Energy, acquired a second plant that uses natural gas as a feedstock. The amount of ammonia production reported by CVR Energy was no longer specific to the use of petroleum coke as a feedstock. To adjust for this, beginning in 2016, the amount of CO_2 from the ammonia production plant located in Kansas that manufactured ammonia from petroleum coke feedstock (as reported under EPA 2021b) is now being used, along with the emission factor of 3.52 metric tons of CO_2 per metric ton of NH_3 to back-calculate the amount of ammonia produced through the use of petroleum coke as feedstock.

The consumption of natural gas and petroleum coke as fossil fuel feedstocks for NH_3 production are adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. More information on this methodology is described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion. See the Planned Improvements section on improvements of reporting fuel and feedstock CO_2 emissions utilizing EPA's GHGRP data to improve consistency with *2006 IPCC Guidelines*.

Total ammonia production data for 2011 through 2020 were obtained from American Chemistry Council (ACC 2021). For years before 2011, ammonia production data (see Table 4-21) were obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2011) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Urea-ammonia nitrate production from petroleum coke for 1990 through 2011 was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007a, 2007b, 2009, 2010, 2011, and 2012) and from *CVR Energy, Inc. Annual Report* (CVR 2012 through 2015) for 2012 through 2015. Urea production data for 1990 through 2008 were obtained from the *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2010 and 2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Urea production values for the years 2011 through 2020 utilize GHGRP data (EPA 2018; EPA 2021a).

Table 4-21: Ammonia Production, Recovered CO_2 Consumed for Urea Production, and Urea Production (kt)

Year	Ammonia Production	Total CO_2 Consumption for Urea Production	Urea Production
1990	15,425	5,463	7,450
2005	10,143	3,865	5,270
2016	12,305	5,419	7,390
2017	14,070	6,622	9,030
2018	16,010	7,847	10,700
2019	16,410	8,360	11,400
2020	16,855	8,433	11,500

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for ammonia production spliced activity data from different sources: U. S. Census Bureau data for 1990 through 2010, and ACC data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock. Uncertainties are also associated with ammonia production estimates and the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. Uncertainty is also associated with the representativeness of the emission factor used for the petroleum coke-based ammonia process. It is also assumed that ammonia and urea are produced at co-located plants from the same natural gas raw material. The uncertainty of the total urea production activity data, based on USGS *Minerals Yearbook: Nitrogen* data, is a function of the reliability of reported production data and is influenced by the completeness of the survey responses. EPA assigned a default uncertainty range of ±5 percent for both ammonia production and the emission factor used for the petroleum coke-based ammonia process, consistent with the ranges in Section 3.2.3.2 of the *2006 IPCC Guidelines*, and ±10 percent for urea production, based on expert judgment.

Recovery of CO_2 from ammonia production plants for purposes other than urea production (e.g., commercial sale, etc.) has not been considered in estimating the CO_2 emissions from ammonia production, as data concerning the disposition of recovered CO_2 are not available. Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere; however, for reporting purposes, CO_2 consumption for urea production is provided in this chapter.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-22. Carbon dioxide emissions from ammonia production in 2020 were estimated to be between 11.4 and 14.1 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below and 11 percent above the emission estimate of 12.7 MMT CO_2 Eq.

Table 4-22: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production	CO_2	12.7	11.4	14.1	-10%	+11%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied to ammonia production emission estimates consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to ammonia facilities can be found under Subpart G (Ammonia Production) of the regulation (40 CFR Part 98).[24] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[25] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea produced at ammonia production facilities can be found under Section 4.5 Urea Consumption for Non-Agricultural Purposes.

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[24] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[25] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

Future improvements involve continuing to evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for the Ammonia Production source category, in particular new facility-level reporting data from updated reporting requirements finalized in October of 2014 (79 FR 63750) and December 2016 (81 FR 89188)[26] that include facility-level ammonia production data and feedstock consumption. The data were first reported by facilities in 2018 and available post-verification in 2019 to assess for use in future Inventories, if the data meet GHGRP CBI aggregation criteria. The data are still being evaluated and will be incorporated in future Inventory reports, if possible. Particular attention will be made to ensure time-series consistency of the emission estimates presented in future Inventory reports, along with application of appropriate category-specific QC procedures consistent with IPCC and UNFCCC guidelines. For example, data reported in 2018 will reflect activity in 2017 and may not be representative of activity in prior years of the time series. This assessment is required as the new GHGRP data associated with new requirements are only applicable starting with reporting for calendar year 2017, and thus are not available for all inventory years (i.e., 1990 through 2016) as required for this Inventory.

In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[27] Specifically, the planned improvements include assessing the anticipated new data to update the emission factors to include both fuel and feedstock CO_2 emissions to improve consistency with *2006 IPCC Guidelines,* in addition to reflecting CO_2 capture and storage practices (beyond use of CO_2 for urea production). Methodologies will also be updated if additional ammonia production plants are found to use hydrocarbons other than natural gas for ammonia production. Due to limited resources and ongoing data collection efforts, this planned improvement is still in development and is not incorporated into this Inventory. This is a long-term planned improvement.

4.6 Urea Consumption for Non-Agricultural Purposes

Urea is produced using ammonia (NH_3) and carbon dioxide (CO_2) as raw materials. All urea produced in the United States is assumed to be produced at ammonia production facilities where both ammonia and CO_2 are generated. There were 35 plants producing ammonia in the United States in 2020, with two additional plants sitting idle for the entire year (USGS 2021).

The chemical reaction that produces urea is:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

This section accounts for CO_2 emissions associated with urea consumed exclusively for non-agricultural purposes. Emissions of CO_2 resulting from agricultural applications of urea are accounted for in Section 5.6 Urea Fertilization (CRF Source Category 3H) of the Agriculture chapter.

The industrial applications of urea include its use in adhesives, binders, sealants, resins, fillers, analytical reagents, catalysts, intermediates, solvents, dyestuffs, fragrances, deodorizers, flavoring agents, humectants and dehydrating agents, formulation components, monomers, paint and coating additives, photosensitive agents, and surface treatments agents. In addition, urea is used for abating nitrogen oxide (NO_x) emissions from coal-fired power plants and diesel transportation motors.

Emissions of CO_2 from urea consumed for non-agricultural purposes in 2020 were estimated to be 6.0 MMT CO_2 Eq. (5,983 kt) and are summarized in Table 4-23 and Table 4-24. Net CO_2 emissions from urea consumption for

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[26] See https://www.epa.gov/ghgreporting/historical-rulemakings.

[27] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

non-agricultural purposes have increased by approximately 58 percent from 1990 to 2020 and decreased by approximately 1.0 percent from 2019 to 2020.

Table 4-23: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Urea Consumption	3.8	3.7	5.3	5.2	6.0	6.0	6.0

Table 4-24: CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (kt)

Source	1990	2005	2016	2017	2018	2019	2020
Urea Consumption	3,784	3,653	5,330	5,182	6,030	6,044	5,983

Methodology and Time-Series Consistency

Emissions of CO_2 resulting from urea consumption for non-agricultural purposes are estimated by multiplying the amount of urea consumed in the United States for non-agricultural purposes by a factor representing the amount of CO_2 used as a raw material to produce the urea. This method is based on the assumption that all of the carbon in urea is released into the environment as CO_2 during use, consistent with the Tier 1 method used to estimate emissions from ammonia production in the *2006 IPCC Guidelines* (IPCC 2006) which states that the "CO_2 recovered [from ammonia production] for downstream use can be estimated from the quantity of urea produced where CO_2 is estimated by multiplying urea production by 44/60, the stoichiometric ratio of CO_2 to urea."

The amount of urea consumed for non-agricultural purposes in the United States is estimated by deducting the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Agriculture chapter (see Table 5-25), from the total domestic supply of urea as reported in Table 4-25. The domestic supply of urea is estimated based on the amount of urea produced plus urea imports and minus urea exports. A factor of 0.733 tons of CO_2 per ton of urea consumed is then applied to the resulting supply of urea for non-agricultural purposes to estimate CO_2 emissions from the amount of urea consumed for non-agricultural purposes. The 0.733 tons of CO_2 per ton of urea emission factor is based on the stoichiometry of carbon in urea. This corresponds to a stoichiometric CO_2 to urea factor of 44/60, assuming complete conversion of carbon in urea to CO_2 (IPCC 2006; EFMA 2000).

Urea production data for 1990 through 2008 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Nitrogen* (USGS 1994 through 2009a). Urea production data for 2009 through 2010 were obtained from the U.S. Census Bureau (2011). The U.S. Census Bureau ceased collection of urea production statistics in 2011. Starting with the 1990 through 2017 Inventory report, EPA began utilizing urea production data from EPA's GHGRP to estimate emissions. Urea production values in the current Inventory report utilize GHGRP data for the years 2011 through 2020 (EPA 2018; EPA 2021a; EPA 2021b).

Urea import data for 2020 were not available at the time of publication and were estimated using 2019 values. Urea import data for 2013 to 2019 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2021a). Urea import data for 2011 and 2012 were taken from *U.S. Fertilizer Import/Exports* from the United States Department of Agriculture (USDA) Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012. Urea import data for the previous years were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for 1997 through 2010 (U.S. Census Bureau 2001 through 2011), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-25).

Urea export data for 2020 were not available at the time of publication and were estimated using 2019 values. Urea export data for 2013 to 2019 were obtained from the USGS *Minerals Yearbook: Nitrogen* (USGS 2021a). Urea export data for 1990 through 2012 were taken from *U.S. Fertilizer Import/Exports* from USDA Economic Research Service Data Sets (U.S. Department of Agriculture 2012). USDA suspended updates to this data after 2012.

Table 4-25: Urea Production, Urea Applied as Fertilizer, Urea Imports, and Urea Exports (kt)

Year	Urea Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports	Urea Consumed for Non-Agricultural Purposes
1990	7,450	3,296	1,860	854	5,160
2005	5,270	4,779	5,026	536	4,981
2016	7,390	6,381	6,580	321	7,268
2017	9,030	6,678	5,510	795	7,067
2018	10,700	6,844	5,110	743	8,223
2019	11,400	7,009	4,410	559	8,242
2020	11,500	7,193	4,410	559	8,158

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for urea consumption for non-agricultural purposes spliced activity data from different sources: USGS data for 1990 through 2008, U. S. Census Bureau data for 2009 and 2010, and GHGRP data beginning in 2011. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

There is limited publicly available data on the quantities of urea produced and consumed for non-agricultural purposes. Therefore, the amount of urea used for non-agricultural purposes is estimated based on a balance that relies on estimates of urea production, urea imports, urea exports, and the amount of urea used as fertilizer. The primary uncertainties associated with this source category are associated with the accuracy of these estimates as well as the fact that each estimate is obtained from a different data source. Because urea production estimates are no longer available from the USGS, there is additional uncertainty associated with urea produced beginning in 2011. There is also uncertainty associated with the assumption that all of the carbon in urea is released into the environment as CO_2 during use.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-26. Carbon dioxide emissions associated with urea consumption for non-agricultural purposes during 2020 were estimated to be between 5.1 and 6.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 14 percent below and 14 percent above the emission estimate of 6.0 MMT CO_2 Eq.

Table 4-26: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Consumption for Non-Agricultural Purposes (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Consumption for Non-Agricultural Purposes	CO_2	6.0	5.1	6.8	-14%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to reporting of urea production occurring at ammonia facilities can be found under Subpart G (Ammonia Manufacturing) of the regulation (40 CFR Part 98).[28] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[29] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported urea production data against external datasets including the USGS *Minerals Yearbook* data. The comparison shows consistent trends in urea production over time.

Recalculations Discussion

Based on updated quantities of urea applied for agricultural uses for 2014-2019, updated urea imports from USGS for 2018 and 2019, and updated urea exports from USGS for 2018 and 2019, recalculations were performed for 2014 through 2019. Compared to the previous Inventory, CO_2 emissions from urea consumption for non-agricultural purposes increased by less than 1 percent (2 kt CO_2) for 2014, 1.6 percent (73 kt CO_2) for 2015, 3.9 percent (198 kt CO_2) for 2016, 3.1 percent (154 kt CO_2) for 2017, and 3.0 percent (173 kt CO_2) for 2018 and decreased by 2.9 percent (178 kt CO_2) for 2019.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

4.7 Nitric Acid Production (CRF Source Category 2B2)

Nitrous oxide (N_2O) is emitted during the production of nitric acid (HNO_3), an inorganic compound used primarily to make synthetic commercial fertilizers. Nitric acid is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is manufactured by the high-temperature catalytic oxidation of ammonia (EPA 1998). There are two different nitric acid production methods: weak nitric acid and high-strength nitric acid. The first method utilizes oxidation, condensation, and absorption to produce nitric acid at concentrations between 30 and 70 percent nitric acid. High-strength acid (90 percent or greater nitric acid) can be produced from dehydrating, bleaching, condensing, and absorption of the weak nitric acid. Most U.S. plants were built between 1960 and 2000. As of 2020, there were 32 active nitric acid production plants, including one high-strength nitric acid production plant in the United States (EPA 2010; EPA 2021).

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[28] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[29] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

The basic process technology for producing nitric acid has not changed significantly over time. During this process, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere. Emissions from fuels consumed for energy purposes during the production of nitric acid are included in the Energy chapter.

Nitric acid is made from the reaction of ammonia (NH_3) with oxygen (O_2) in two stages. The overall reaction is:

$$4NH_3 + 8O_2 \rightarrow 4HNO_3 + 4H_2$$

Currently, the nitric acid industry in the United States controls emissions of NO and NO_2 (i.e., NO_x), using a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. Five nitric acid plants had NSCR systems installed between 1964 and 1977, over half due to the finalization of the Nitric Acid Plant New Source Performance Standards (NSPS) which went into effect in 1971. Four additional nitric acid plants had NSCR systems installed between 2016 and 2018, as a result of EPA Consent Decrees to control NO_X emissions more effectively. NSCR systems are used in approximately one-third of the weak acid production plants. For N_2O abatement, U.S. facilities are using both tertiary (i.e., NSCR and SCR) and secondary controls (i.e., catalysts added to the ammonia reactor to lessen potential N_2O production).

Emissions from the production of nitric acid are generally directly proportional to the annual amount of nitric acid produced because emissions are calculated as the product of the total annual production and plant-specific emission factors. There are a few instances, however, where that relationship has not been directly proportional. For example, in 2015 and 2019, nitric acid production decreased and emissions increased, compared to the respective preceding years. N_2O emissions for those years are calculated based on data from the GHGRP as discussed in the Methodology section below. According to data from plants reporting to GHGRP, plant-specific operations can affect the emission factor used, including: (1) site-specific fluctuations in ambient temperature and humidity, (2) catalyst age and condition, (3) process changes, (4) the addition or removal of abatement technologies, and (5) the number of nitric acid trains. Changes in those operating conditions for the years in question (2015 and 2018) caused changes in emission factors and, therefore, the emissions to change disproportionally to production in those years.

Nitrous oxide emissions from this source were estimated to be 9.3 MMT CO_2 Eq. (31 kt of N_2O) in 2020 (see Table 4-27). Emissions from nitric acid production have decreased by 23 percent since 1990, while production has increased by 11 percent over the same time period (see Table 4-27). Emissions have decreased by 36 percent since 1997, the highest year of production in the time series. The primary use of nitric acid is to produce synthetic fertilizers, and in 2020, the fertilizer industry was considered part of the critical chemical sector by the U.S. Department of Homeland Security, which minimized the impact of the COVID-19 pandemic on nitric acid production and emissions (USGS 2021).

Table 4-27: N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	12.1	41
2005	11.3	38
2016	10.1	34
2017	9.3	31
2018	9.6	32
2019	10.0	34
2020	9.3	31

Methodology and Time-Series Consistency

Emissions of N_2O were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and a country-specific method utilizing EPA's GHGRP. The *2006 IPCC Guidelines* Tier 2 method was used to estimate emissions from nitric acid production for 1990 through 2009, and a country-specific approach similar to the IPCC Tier 3 method was used to estimate N_2O emissions for 2010 through 2020.

For this Inventory, EPA reviewed GHGRP facility-level information on the installation date of all N_2O abatement equipment (EPA 2021). Revisions to GHGRP reporting requirements were finalized in December 2016, and this information was first reported by facilities in 2018 and available post-verification in 2019. EPA verified that all reported N_2O abatement equipment had already been incorporated into the estimation of N_2O emissions from nitric acid production over the full time series.

2010 through 2020

Process N_2O emissions and nitric acid production data were obtained directly from EPA's GHGRP for 2010 through 2020 by aggregating reported facility-level data (EPA 2021).

Since 2010, in the United States, all nitric acid facilities that produce weak nitric acid (30 to 70 percent) have been required to report annual greenhouse gas emissions data to EPA as per the requirements of the GHGRP (Subpart V). Beginning with 2018, the rule was changed to include facilities that produce nitric acid of any strength. The only facility that produces high-strength nitric acid also produces weak nitric acid. All greenhouse gas emissions from nitric acid production originate from the production of weak nitric acid.

Process emissions and nitric acid production reported to the GHGRP provide complete estimates of greenhouse gas emissions for the United States because there are no reporting thresholds. While facilities are allowed to stop reporting to the GHGRP if the total reported emissions from nitric acid production are less than 25,000 metric tons CO_2 Eq. per year for five consecutive years or less than 15,000 metric tons CO_2 Eq. per year for three consecutive years, no facilities have stopped reporting as a result of these provisions.[30] All nitric acid facilities are required to calculate process emissions using a site-specific emission factor that is the average of the emission factor determined through annual performance tests for each nitric acid train under typical operating conditions or by directly measuring N_2O emissions using monitoring equipment.[31]

Emissions from facilities vary from year to year, depending on the amount of nitric acid produced with and without abatement technologies and other conditions affecting the site-specific emission factor. To maintain consistency across the time series and with the rounding approaches taken by other data sets, GHGRP nitric acid data are rounded for consistency and are shown in Table 4-28.

1990 through 2009

Using GHGRP data for 2010,[32] country-specific N_2O emission factors were calculated for nitric acid production with abatement and without abatement (i.e., controlled and uncontrolled emission factors). The following 2010 emission factors were derived for production with abatement and without abatement: 3.3 kg N_2O/metric ton HNO_3 produced at plants using abatement technologies (e.g., tertiary systems such as NSCR systems) and 5.99 kg N_2O/metric ton HNO_3 produced at plants not equipped with abatement technology. Country-specific weighted emission factors were derived by weighting these emission factors by percent production with abatement and without abatement over time periods 1990 through 2008 and 2009. These weighted emission factors were used to estimate N_2O emissions from nitric acid production for years prior to the availability of GHGRP data (i.e., 1990 through 2008 and 2009). A separate weighted emission factor is included for 2009 due to data availability for that year. At that time, EPA had initiated compilation of a nitric acid database to improve estimation of emissions from

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[30] See 40 CFR 98.2(i)(1) and 40 CFR 98.2(i)(2) for more information about these provisions.

[31] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance tests, and must follow associated QA/QC procedures consistent with category-specific QC of direct emission measurements during these performance tests.

[32] National N_2O process emissions, national production, and national share of nitric acid production with abatement and without abatement technology was aggregated from the GHGRP facility-level data for 2010 to 2017 (i.e., percent production with and without abatement).

this industry and obtained updated information on application of controls via review of permits and outreach with facilities and trade associations. The research indicated recent installation of abatement technologies at additional facilities.

Based on the available data, it was assumed that emission factors for 2010 would be more representative of operating conditions in 1990 through 2009 than more recent years. Initial review of historical data indicates that percent production with and without abatement can change over time and from year to year due to changes in application of facility-level abatement technologies, maintenance of abatement technologies, and plant closures and start-ups (EPA 2012, 2013; Desai 2012; CAR 2013). In this Inventory, EPA verified the installation dates of N_2O abatement technologies for all facilities based on GHGRP facility-level information (EPA 2021), as noted above. Due to the lack of information on abatement equipment utilization, it is assumed that once abatement technology was installed in facilities, the equipment was consistently operational for the duration of the time series considered in this report (especially NSCRs).

The country-specific weighted N_2O emission factors were used in conjunction with annual production to estimate N_2O emissions for 1990 through 2009, using the following equations:

Equation 4-4: *2006 IPCC Guidelines* Tier 3: N_2O Emissions From Nitric Acid Production (Equation 3.6)

$$E_i = P_i \times EF_{weighted,i}$$

$$EF_{weighted,i} = \left[\left(\%P_{c,i} \times EF_c\right) + \left(\%P_{unc,i} \times EF_{unc}\right)\right]$$

where,

E_i = Annual N_2O Emissions for year i (kg/yr)
P_i = Annual nitric acid production for year i (metric tons HNO_3)
$EF_{weighted,i}$ = Weighted N_2O emission factor for year i (kg N_2O/metric ton HNO_3)
$\%P_{c,i}$ = Percent national production of HNO_3 with N_2O abatement technology (%)
EF_c = N_2O emission factor, with abatement technology (kg N_2O/metric ton HNO_3)
$\%P_{unc,i}$ = Percent national production of HNO_3 without N_2O abatement technology (%)
EF_{unc} = N_2O emission factor, without abatement technology (kg N_2O/metric ton HNO_3)
i = year from 1990 through 2009

- For 2009: Weighted N_2O emission factor = 5.46 kg N_2O/metric ton HNO_3.
- For 1990 through 2008: Weighted N_2O emission factor = 5.66 kg N_2O/metric ton HNO_3.

Nitric acid production data for the United States for 1990 through 2009 were obtained from the U.S. Census Bureau (U.S. Census Bureau 2008, 2009, 2010a, 2010b) (see Table 4-28). Publicly available information on plant-level abatement technologies was used to estimate the shares of nitric acid production with and without abatement for 2008 and 2009 (EPA 2012, 2013; Desai 2012; CAR 2013). In previous Inventory reports, EPA conducted a review of operating permits to obtain more information on the use or installation of abatement technologies for 1990 through 2007; therefore, the share of national production with and without abatement for 2008 was assumed to be constant for 1990 through 2007. As noted above, EPA used GHGRP facility-level information to verify that all reported N_2O abatement equipment had already been incorporated into the estimation of N_2O emissions from nitric acid production over the full time series (EPA 2021).

Table 4-28: Nitric Acid Production (kt)

Year	kt
1990	7,200
2005	6,710
2016	7,810
2017	7,780
2018	8,210
2019	8,080
2020	7,970

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for nitric acid production spliced activity data from two different sources: U. S. Census Bureau production data for 1990 through 2009 and GHGRP production data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with the parameters used to estimate N_2O emissions includes the share of U.S. nitric acid production attributable to each emission abatement technology over the time series (especially prior to 2010), and the associated emission factors applied to each abatement technology type. While some information has been obtained through outreach with industry associations, limited information is available over the time series (especially prior to 2010) for a variety of facility level variables, including plant-specific production levels, plant production technology (e.g., low, high pressure, etc.), and abatement technology destruction and removal efficiency rates. Production data prior to 2010 were obtained from National Census Bureau, which does not provide uncertainty estimates with their data. Facilities reporting to EPA's GHGRP must measure production using equipment and practices used for accounting purposes. While emissions are often directly proportional to production, the emission factor for individual facilities can vary significantly from year to year due to site-specific fluctuations in ambient temperature and humidity, catalyst age and condition, nitric acid production process changes, the addition or removal of abatement technologies, and the number of nitric acid trains at the facility. At this time, EPA does not estimate uncertainty of the aggregated facility-level information. As noted in the QA/QC and verification section below, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. The annual production reported by each nitric acid facility under EPA's GHGRP and then aggregated to estimate national N_2O emissions is assumed to have low uncertainty. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, consistent with section 3.4.3.1 of the *2006 IPCC Guidelines*, and ±2 percent for nitric acid production, consistent with section 3.3.3.2 of the *2006 IPCC Guidelines*.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-29. Nitrous oxide emissions from nitric acid production were estimated to be between 8.8 and 9.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the 2020 emissions estimate of 9.3 MMT CO_2 Eq.

Table 4-29: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Nitric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]	
			(MMT CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N_2O	9.3	8.8	9.8	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to nitric acid facilities can be found under Subpart V: Nitric Acid Production of the GHGRP regulation (40 CFR Part 98).[33]

The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process that is tailored to the Subpart (e.g., combination of electronic checks including range checks, statistical checks, algorithm checks, year-to-year comparison checks, along with manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent. Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred (EPA 2015).[34] EPA's review of observed trends noted that while emissions have generally mirrored production, in 2015 and 2019 nitric acid production decreased compared to the previous year and emissions increased. While review is ongoing, based on feedback from the verification process to date, these changes are due to facility-specific changes (e.g., in the nitric production process and management of abatement equipment).

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

Pending resources, EPA is considering a near-term improvement to estimates and associated characterization of uncertainty. In the short-term, with 10 years of EPA's GHGRP data, EPA anticipates completing updates of category-specific QC procedures. EPA also anticipates making improvements to both qualitative and quantitative uncertainty estimates.

4.8 Adipic Acid Production (CRF Source Category 2B3)

Adipic acid is produced through a two-stage process during which nitrous oxide (N_2O) is generated in the second stage. Emissions from fuels consumed for energy purposes during the production of adipic acid are accounted for in the Energy chapter. The first stage of manufacturing usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce

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[33] See Subpart V monitoring and reporting regulation http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[34] See GHGRP Verification Factsheet https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

adipic acid. Nitrous oxide is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). The second stage is represented by the following chemical reaction:

$$(CH_2)_5CO(cyclohexanone) + (CH_2)_5CHOH(cyclohexanol) + wHNO_3 \\ \rightarrow HOOC(CH_2)_4COOH(adipic\ acid) + xN_2O + yH_2O$$

Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two major adipic acid-producing plants had N_2O abatement technologies in place and, as of 1998, three major adipic acid production facilities had control systems in place (Reimer et al. 1999). In 2020, catalytic reduction, non-selective catalytic reduction (NSCR), and thermal reduction abatement technologies were applied as N_2O abatement measures at adipic acid facilities (EPA 2021).

Worldwide, only a few adipic acid plants exist. The United States, Europe, and China are the major producers, with the United States accounting for the largest share of global adipic acid production capacity in recent years. In 2020, the United States had two companies with a total of two adipic acid production facilities (one in Texas and one in Florida), following the ceased operations of a third major production facility at the end of 2015 (EPA 2021).

Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6; 9 percent is used in the production of polyester polyols; 4 percent is used in the production of plasticizers; and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food grade adipic acid is used to provide some foods with a “tangy” flavor (Thiemens and Trogler 1991).

National adipic acid production has decreased by approximately 7 percent over the period of 1990 through 2020, to approximately 700,000 metric tons (ACC 2021). Nitrous oxide emissions from adipic acid production were estimated to be 8.3 MMT CO_2 Eq. (28 kt N_2O) in 2020 (see Table 4-30). Over the period 1990 through 2020, facilities have reduced emissions by 45 percent due to the widespread installation of pollution control measures in the late 1990s. The COVID-19 pandemic may have partially influenced the decrease in adipic acid production between 2019 and 2020.

Significant changes in the amount of time that the N_2O abatement device at one facility was in operation has been the main cause of fluctuating emissions in recent years. These fluctuations are most evident for years where trends in emissions and adipic acid production were not directly proportional: (1) between 2016 and 2017, (2) between 2017 and 2018, and (3) between 2019 and 2020. As noted above, changes in control measures and abatement technologies at adipic acid production facilities, including maintenance of equipment, can result in annual emission fluctuations. Little additional information is available on drivers of trends, and the amount of adipic acid produced is not reported under EPA’s GHGRP.

Table 4-30: N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	15.2	51
2005	7.1	24
2016	7.1	24
2017	7.5	25
2018	10.5	35
2019	5.3	18
2020	8.3	28

Methodology and Time-Series Consistency

Emissions are estimated using both Tier 2 and Tier 3 methods consistent with the *2006 IPCC Guidelines.* Due to confidential business information (CBI), plant names are not provided in this section; therefore, the four adipic acid-producing facilities that have operated over the time series will be referred to as Plants 1 through 4. Overall, as noted above, the two currently operating facilities use catalytic reduction, NSCR, and thermal reduction abatement technologies.

2010 through 2020

All emission estimates for 2010 through 2020 were obtained through analysis of GHGRP data (EPA 2010 through 2021), which is consistent with the *2006 IPCC Guidelines* Tier 3 method. Facility-level greenhouse gas emissions data were obtained from EPA's GHGRP for the years 2010 through 2020 (EPA 2010 through 2021) and aggregated to national N_2O emissions. Consistent with IPCC Tier 3 methods, all adipic acid production facilities are required to either calculate N_2O emissions using a facility-specific emission factor developed through annual performance testing under typical operating conditions or directly measure N_2O emissions using monitoring equipment.[35]

1990 through 2009

For years 1990 through 2009, which were prior to EPA's GHGRP reporting, for both Plants 1 and 2, emission estimates were obtained directly from the plant engineers and account for reductions due to control systems in place at these plants during the time series. These prior estimates are considered CBI and hence are not published (Desai 2010, 2011). These estimates were based on continuous process monitoring equipment installed at the two facilities.

For Plant 4, 1990 through 2009 N_2O emissions were estimated using the following Tier 2 equation from the *2006 IPCC Guidelines*:

Equation 4-5: *2006 IPCC Guidelines* Tier 2: N_2O Emissions From Adipic Acid Production (Equation 3.8)

$$E_{aa} = Q_{aa} \times EF_{aa} \times (1 - [DF \times UF])$$

where,

E_{aa} = N_2O emissions from adipic acid production, metric tons
Q_{aa} = Quantity of adipic acid produced, metric tons
EF_{aa} = Emission factor, metric ton N_2O/metric ton adipic acid produced
DF = N_2O destruction factor
UF = Abatement system utility factor

The adipic acid production is multiplied by an emission factor (i.e., N_2O emitted per unit of adipic acid produced), which has been estimated to be approximately 0.3 metric tons of N_2O per metric ton of product (IPCC 2006). The "N_2O destruction factor" in the equation represents the percentage of N_2O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Plant-specific production data for Plant 4 were obtained across the time series through personal communications (Desai 2010, 2011). The plant-specific production data were then used for calculating emissions as described above.

For Plant 3, 2005 through 2009 emissions were obtained directly from the plant (Desai 2010, 2011). For 1990 through 2004, emissions were estimated using plant-specific production data and the IPCC factors as described

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[35] Facilities must use standard methods, either EPA Method 320 or ASTM D6348-03 for annual performance testing, and must follow associated QA/QC procedures during these performance tests consistent with category-specific QC of direct emission measurements.

above for Plant 4. Plant-level adipic acid production for 1990 through 2003 was estimated by allocating national adipic acid production data to the plant level using the ratio of known plant capacity to total national capacity for all U.S. plants (ACC 2020; CMR 2001, 1998; CW 1999; C&EN 1992 through 1995). For 2004, actual plant production data were obtained and used for emission calculations (CW 2005).

Plant capacities for 1990 through 1994 were obtained from *Chemical & Engineering News*, “Facts and Figures” and “Production of Top 50 Chemicals” (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter*, “Chemical Profile: Adipic Acid” (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for the year 2000 for three of the plants were updated using *Chemical Market Reporter*, “Chemical Profile: Adipic Acid” (CMR 2001). For 2001 through 2003, the plant capacities for three plants were held constant at year 2000 capacities. Plant capacity for 1999 to 2003 for the one remaining plant was kept the same as 1998.

National adipic acid production data (see Table 4-31) from 1990 through 2020 were obtained from the American Chemistry Council (ACC 2021).

Table 4-31: Adipic Acid Production (kt)

Year	kt
1990	755
2005	865
2016	860
2017	830
2018	825
2019	810
2020	700

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for adipic acid production spliced activity data from multiple sources: plant-specific emissions data and publicly available plant capacity data for 1990 through 2009 and GHGRP emission data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap, with findings that the data sets were consistent and adjustments were not needed.

Uncertainty

Uncertainty associated with N_2O emission estimates includes the methods used by companies to monitor and estimate emissions. While some information has been obtained through outreach with facilities, limited information is available over the time series on these methods, abatement technology destruction and removal efficiency rates, and plant-specific production levels. EPA assigned an uncertainty range of ±5 percent for facility-reported N_2O emissions, consistent with section 3.4.3.1 of the *2006 IPCC Guidelines*.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-32. Nitrous oxide emissions from adipic acid production for 2020 were estimated to be between 7.9 and 8.7 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 5 percent below to 5 percent above the 2020 emission estimate of 8.3 MMT CO_2 Eq.

Table 4-32: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]	
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)	(%)

			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	8.3	7.9	8.7	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to adipic acid facilities can be found under Subpart E (Adipic Acid Production) of the GHGRP regulation (40 CFR Part 98).[36] The main QA/QC activities are related to annual performance testing, which must follow either EPA Method 320 or ASTM D6348-03. EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[37] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year comparisons of reported data.

Recalculations Discussion

Recalculations of adipic acid emissions were performed for the 2016 through 2019 portion of the time series due to GHGRP resubmittals for those years. For years 2016 through 2018, the emissions increased by 0.4 MMT CO_2 Eq. (1.6 percent), 0.3 MMT CO_2 Eq. (1.2 percent), and 0.6 MMT CO_2 Eq. (1.8 percent), respectively. For year 2019, the emissions decreased by 0.1 MMT CO_2 Eq. (0.3 percent).

Planned Improvements

EPA plans to review GHGRP facility reported information on the date of abatement technology installation in order to better reflect trends and changes in emissions abatement within the industry across the time series. To date, the facility using the facility-specific emission factor developed through annual performance testing has reported no utilization of N_2O abatement technology. The facility using direct measurement of N_2O emissions has reported the use of N_2O abatement technology but is not required to report the date of installation.

4.9 Caprolactam, Glyoxal and Glyoxylic Acid Production (CRF Source Category 2B4)

Caprolactam

Caprolactam ($C_6H_{11}NO$) is a colorless monomer produced for nylon-6 fibers and plastics. A substantial proportion of the fiber is used in carpet manufacturing. Most commercial processes used for the manufacture of caprolactam

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[36] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[37] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

begin with benzene, but toluene can also be used. The production of caprolactam can give rise to significant emissions of nitrous oxide (N_2O).

During the production of caprolactam, emissions of N_2O can occur from the ammonia oxidation step, emissions of carbon dioxide (CO_2) from the ammonium carbonate step, emissions of sulfur dioxide (SO_2) from the ammonium bisulfite step, and emissions of non-methane volatile organic compounds (NMVOCs). Emissions of CO_2, SO_2 and NMVOCs from the conventional process are unlikely to be significant in well-managed plants. Modified caprolactam production processes are primarily concerned with elimination of the high volumes of ammonium sulfate that are produced as a byproduct of the conventional process (IPCC 2006).

In the most commonly used process where caprolactam is produced from benzene, benzene is hydrogenated to cyclohexane which is then oxidized to produce cyclohexanone ($C_6H_{10}O$). The classical route (Raschig process) and basic reaction equations for production of caprolactam from cyclohexanone are (IPCC 2006):

$$Oxidation\ of\ NH_3\ to\ NO/NO_2$$

$$\downarrow$$

$$NH_3\ reacted\ with\ CO_2/H_2O\ to\ yield\ ammonium\ carbonate\ (NH_4)_2CO_3$$

$$\downarrow$$

$$(NH_4)_2CO_3\ reacted\ with\ NO/NO_2\ (from\ NH_3\ oxidation)\ to\ yield\ ammonium\ nitrite\ (NH_4NO_2)$$

$$\downarrow$$

$$NH_3\ reacted\ with\ SO_2/H_2O\ to\ yield\ ammonium\ bisulphite\ (NH_4HSO_3)$$

$$\downarrow$$

$$NH_4NO_2\ and\ (NH_4HSO_3)\ reacted\ to\ yield\ hydroxylamine\ disulphonate\ (NOH(SO_3NH_4)_2)$$

$$\downarrow$$

$$(NOH(SO_3NH_4)_2)\ hydrolised\ to\ yield\ hydroxylamine\ sulphate\ ((NH_2OH)_2.H_2SO_4)\ and$$

$$ammonium\ sulphate\ ((NH_4)_2SO_4)$$

$$\downarrow$$

$$Cylohexanone\ reaction:$$

$$C_6H_{10}O\ +\frac{1}{2}(NH_2OH)_2.H_2SO_4(+NH_3\ and\ H_2SO_4) \rightarrow C_6H_{10}NOH\ +(NH_4)_2SO_4\ +H_2O$$

$$\downarrow$$

$$Beckmann\ rearrangement:$$

$$C_6H_{10}NOH\ \ (+H_2SO_4\ and\ SO_2) \rightarrow C_6H_{11}NO.H_2SO_4\ (+4NH_3\ and\ H_2O) \rightarrow C_6H_{11}NO\ +2(NH4)_2SO_4$$

In 2004, three facilities produced caprolactam in the United States (ICIS 2004). Another facility, Evergreen Recycling, was in operation from 2000 to 2001 (ICIS 2004; Textile World 2000) and from 2007 through 2015 (DOE 2011; Shaw 2015). Caprolactam production at Fibrant LLC (formerly DSM Chemicals) in Georgia ceased in 2018 (Cline 2019). As of 2020, two companies in the United States produced caprolactam at two facilities: AdvanSix (formerly Honeywell) in Virginia (AdvanSix 2021) and BASF in Texas (BASF 2021).

Nitrous oxide emissions from caprolactam production in the United States were estimated to be 1.2 MMT CO_2 Eq. (4 kt N_2O) in 2020 (see Table 4-33). National emissions from caprolactam production decreased by approximately 28 percent over the period of 1990 through 2020. Emissions in 2020 decreased by approximately 13 percent from the 2019 levels. While this decrease could be related to the COVID-19 pandemic, caprolactam production has been declining since 2013, with the largest decrease of 15 percent happening between 2016 and 2017.

Table 4-33: N_2O Emissions from Caprolactam Production (MMT CO_2 Eq. and kt N_2O)

Year	MMT CO_2 Eq.	kt N_2O
1990	1.7	6
2005	2.1	7
2016	1.7	6
2017	1.5	5
2018	1.4	5
2019	1.4	5
2020	1.2	4

Glyoxal

Glyoxal is mainly used as a crosslinking agent for vinyl acetate/acrylic resins, disinfectant, gelatin hardening agent, textile finishing agent (permanent-press cotton, rayon fabrics), and wet-resistance additive (paper coatings) (IPCC 2006). It is also used for enhanced oil-recovery. It is produced from oxidation of acetaldehyde with concentrated nitric acid, or from the catalytic oxidation of ethylene glycol, and N_2O is emitted in the process of oxidation of acetaldehyde.

Glyoxal (ethanedial) ($C_2H_2O_2$) is produced from oxidation of acetaldehyde (ethanal) (C_2H_4O) with concentrated nitric acid (HNO_3). Glyoxal can also be produced from catalytic oxidation of ethylene glycol (ethanediol) (CH_2OHCH_2OH).

Glyoxylic Acid

Glyoxylic acid is produced by nitric acid oxidation of glyoxal. Glyoxylic acid is used for the production of synthetic aromas, agrochemicals, and pharmaceutical intermediates (IPCC 2006).

EPA does not currently estimate the emissions associated with the production of Glyoxal and Glyoxylic Acid due to a lack of publicly available information on the industry in the United States. See Annex 5 for additional information.

Methodology and Time-Series Consistency

Emissions of N_2O from the production of caprolactam were calculated using the estimation methods provided by the *2006 IPCC Guidelines*. The *2006 IPCC Guidelines* Tier 1 method was used to estimate emissions from caprolactam production for 1990 through 2020, as shown in this formula:

Equation 4-6: *2006 IPCC Guidelines* Tier 1: N_2O Emissions From Caprolactam Production (Equation 3.9)

$$E_{N_2O} = EF \ x \ CP$$

where,

E_{N_2O} = Annual N_2O Emissions (kg)
EF = N_2O emission factor (default) (kg N_2O/metric ton caprolactam produced)
CP = Caprolactam production (metric tons)

During the caprolactam production process, N_2O is generated as a byproduct of the high temperature catalytic oxidation of ammonia (NH_3), which is the first reaction in the series of reactions to produce caprolactam. The amount of N_2O emissions can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 111.1 metric tons of caprolactam are required to generate one metric ton of N_2O, resulting in an emission factor of 9.0 kg N_2O per metric ton of caprolactam (IPCC

2006). When applying the Tier 1 method, the *2006 IPCC Guidelines* state that it is good practice to assume that there is no abatement of N_2O emissions and to use the highest default emission factor available in the guidelines. In addition, EPA did not find support for the use of secondary catalysts to reduce N_2O emissions, such as those employed at nitric acid plants.

The activity data for caprolactam production (see Table 4-34) from 1990 to 2020 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2021). EPA will continue to analyze and assess alternative sources of production data as a quality control measure.

Table 4-34: Caprolactam Production (kt)

Year	kt
1990	626
2005	795
2016	640
2017	545
2018	530
2019	515
2020	450

Carbon dioxide and methane (CH_4) emissions may also occur from the production of caprolactam, but currently the IPCC does not have methodologies for calculating these emissions associated with caprolactam production.

Methodological approaches, consistent with IPCC guidelines, have been applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

Estimation of emissions of N_2O from caprolactam production can be treated as analogous to estimation of emissions of N_2O from nitric acid production. Both production processes involve an initial step of NH_3 oxidation, which is the source of N_2O formation and emissions (IPCC 2006). Therefore, uncertainties for the default emission factor values in the *2006 IPCC Guidelines* are an estimate based on default values for nitric acid plants. In general, default emission factors for gaseous substances have higher uncertainties because mass values for gaseous substances are influenced by temperature and pressure variations and gases are more easily lost through process leaks. The default values for caprolactam production have a relatively high level of uncertainty due to the limited information available (IPCC 2006).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-35. Nitrous oxide emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production for 2020 were estimated to be between 0.8 and 1.6 MMT CO_2 Eq. at the 95 percent confidence level. These values indicate a range of approximately 31 percent below to 32 percent above the 2020 emission estimate of 1.2 MMT CO_2 Eq.

Table 4-35: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from Caprolactam, Glyoxal and Glyoxylic Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Caprolactam Production	N_2O	1.2	0.8	1.6	-31%	+32%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

Pending resources, EPA will research other available datasets for caprolactam production and industry trends, including facility-level data. EPA continues to research the production process and emissions associated with the production of glyoxal and glyoxylic acid. Preliminary data suggests that glyoxal and glyoxylic acid may no longer be produced domestically and are largely imported to the United States. EPA is working to identify historical data to understand if any production of these chemicals has occurred since 1990. EPA plans to share latest findings from ongoing research for feedback during the next Inventory expert review cycle. During the Expert Review period for the current Inventory report, EPA continued to seek expert solicitation on data available for these emission source categories. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

4.10 Carbide Production and Consumption (CRF Source Category 2B5)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of silicon carbide (SiC), a material used for industrial abrasive applications as well as metallurgical and other non-abrasive applications in the United States. Emissions from fuels consumed for energy purposes during the production of silicon carbide are accounted for in the Energy chapter. Additionally, some metallurgical and non-abrasive applications of SiC are emissive, and while emissions should be accounted for where they occur based on *2006 IPCC Guidelines*, emissions from SiC consumption are accounted for here until additional data on SiC consumption by end-use are available.

To produce SiC, silica sand or quartz (SiO_2) is reacted with carbon (C) in the form of petroleum coke. A portion (about 35 percent) of the carbon contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or carbon monoxide (CO). The overall reaction is shown below, but in practice, it does not proceed according to stoichiometry:

$$SiO_2 + 3C \rightarrow SiC + 2CO \ (+ O_2 \rightarrow 2CO_2)$$

Carbon dioxide and CH_4 are also emitted during the production of calcium carbide, a chemical used to produce acetylene. Carbon dioxide is implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. As noted in Annex 5 to this report, CH_4 emissions from calcium carbide production are not estimated because data are not available. EPA is continuing to investigate the inclusion of these emissions in future Inventory reports.

Markets for manufactured abrasives, including SiC, are heavily influenced by activity in the U.S. manufacturing sector, especially in the aerospace, automotive, furniture, housing, and steel manufacturing sectors. Specific applications of abrasive-grade SiC in 2017 included antislip abrasives, blasting abrasives, bonded abrasives, coated abrasives, polishing and buffing compounds, tumbling media, and wire-sawing abrasives. Approximately 50 percent of SiC is used in metallurgical applications, which include primarily iron and steel production, and other non-abrasive applications, which include use in advanced or technical ceramics and refractories (USGS 1991a through 2020, Washington Mills 2021).

As a result of the economic downturn in 2008 and 2009, demand for SiC decreased in those years. Low-cost imports, particularly from China, combined with high relative operating costs for domestic producers, continue to put downward pressure on the production of SiC in the United States. Consumption of SiC in the United States has recovered somewhat from its low in 2009 (USGS 1991b through 2020).

Silicon carbide was manufactured by two facilities in the United States, one of which produced primarily non-abrasive SiC (USGS 2020). USGS production values for the United States consists of SiC used for abrasives and for metallurgical and other non-abrasive applications (USGS 2020). During the COVID-19 pandemic in 2020, the U.S. Department of Homeland Security considered abrasives manufacturing part of the critical manufacturing sector, and as a result, pandemic “stay-at-home” orders issued in March 2020 did not affect the abrasives manufacturing industry. These plants remained at full operation (USGS 2021). Consumption of SiC, however, decreased by approximately 25 percent due to a sharp decline in imports (U.S. Census Bureau 2005 through 2021).

Carbon dioxide emissions from SiC production and consumption in 2020 were 0.2 MMT CO_2 Eq. (154 kt CO_2), which are about 40 percent lower than emissions in 1990 (243 kt) (see Table 4-36 and Table 4-37). Approximately 59 percent of these emissions resulted from SiC production, while the remainder resulted from SiC consumption. Methane emissions from SiC production in 2020 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4) (see Table 4-36 and Table 4-37). Emissions have not fluctuated greatly in recent years.

Table 4-36: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
Production							
CO_2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	+	+	+	+	+	+	+
Consumption							
CO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-37: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (kt)

Year	1990	2005	2016	2017	2018	2019	2020
Production							
CO_2	170	92	92	92	92	92	92
CH_4	1	+	+	+	+	+	+
Consumption							
CO_2	73	121	78	90	93	84	62

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from the production of SiC were calculated using the Tier 1 method provided by the *2006 IPCC Guidelines*. Annual estimates of SiC production were multiplied by the default emission factors, as shown below:

Equation 4-7: *2006 IPCC Guidelines* Tier 1: Emissions from Carbide Production (Equation 3.11)

$$E_{sc,CO2} = EF_{sc,CO2} \times Q_{sc}$$

$$E_{sc,CH4} = EF_{sc,CH4} \times Q_{sc} \times \left(\frac{1\ metric\ ton}{1000\ kg}\right)$$

where,

$E_{sc,CO2}$ = CO_2 emissions from production of SiC, metric tons
$EF_{sc,CO2}$ = Emission factor for production of SiC, metric ton CO_2/metric ton SiC
Q_{sc} = Quantity of SiC produced, metric tons
$E_{sc,CH4}$ = CH_4 emissions from production of SiC, metric tons
$EF_{sc,CH4}$ = Emission factor for production of SiC, kilogram CH_4/metric ton SiC

Emission factors were taken from the *2006 IPCC Guidelines*:

- 2.62 metric tons CO_2/metric ton SiC
- 11.6 kg CH_4/metric ton SiC

Production data for metallurgical and other non-abrasive applications of SiC are not available; therefore, both CO_2 and CH_4 estimates for SiC are based solely upon production data for SiC for industrial abrasive applications.

Silicon carbide industrial abrasives production data for 1990 through 2017 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2017). Production data for 2018 through 2020 were obtained from the *Mineral Commodity Summaries: Abrasives (Manufactured)* (USGS 2021). Silicon carbide production data published by USGS have been rounded to the nearest 5,000 metric tons to avoid disclosing company proprietary data. For the period 1990 through 2001, reported USGS production data include production from a facility located in Canada that ceased operations in 2001. Using SiC data from Canada (UNFCCC GHG Data Interface 2021), U.S. SiC production for 1990 through 2001 was revised to reflect only U.S. production. SiC consumption for the entire time series is estimated using USGS consumption data (USGS 1991b through 2020) and data from the U.S. International Trade Commission (USITC) database on net imports and exports of SiC(U.S. Census Bureau 2005 through 2021) (see Table 4-38). Total annual SiC consumption (utilization) was estimated by subtracting annual exports of SiC from the annual total of national SiC production and net imports.

Emissions of CO_2 from SiC consumption for metallurgical uses were calculated by multiplying the annual utilization of SiC for metallurgical uses (reported annually in the USGS *Minerals Yearbook: Silicon*) by the carbon content of SiC (30.0 percent), which was determined according to the molecular weight ratio of SiC. Because USGS withheld consumption data for metallurgical uses from publication for 2017 and 2018 due to concerns of disclosing company-specific sensitive information, SiC consumption for 2017 and 2018 were estimated using 2016 values.

Emissions of CO_2 from SiC consumption for other non-abrasive uses were calculated by multiplying the annual SiC consumption for non-abrasive uses by the carbon content of SiC (30 percent). The annual SiC consumption for non-abrasive uses was calculated by multiplying the annual SiC consumption (production plus net imports) by the percentage used in metallurgical and other non-abrasive uses (50 percent) (USGS 1991a through 2017) and then subtracting the SiC consumption for metallurgical use.

The petroleum coke portion of the total CO_2 process emissions from silicon carbide production is adjusted for within the Energy chapter, as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Table 4-38: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	65,000	132,465
2005	35,000	220,149
2016	35,000	142,104
2017	35,000	163,492
2018	35,000	168,526
2019	35,000	152,410
2020	35,000	113,736

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative is to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. However, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also uncertainty associated with the use or destruction of CH_4 generated from the process, in addition to uncertainty associated with levels of production, net imports, consumption levels, and the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-39. Silicon carbide production and consumption CO_2 emissions from 2020 were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.15 MMT CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 9 percent above the emission estimate of 0.01 MMT CO_2 Eq. at the 95 percent confidence level.

Table 4-39: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.15	0.14	0.17	-9%	+9%
Silicon Carbide Production	CH_4	+	+	+	-9%	+9%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

For the period 1990 through 2001, reported USGS production data included production from two facilities located in Canada. Using SiC data from Canada (UNFCCC GHG Data Interface 2021),[38] U.S. SiC production for 1990 through 2001 was recalculated to reflect only U.S. production. Using the recalculated production values, CO_2 emissions decreased by 25 to 127 kt CO_2 per year, a decrease in emissions of between about 10 percent and 45 percent. Estimates for CH_4 emissions decreased by about 0.1 to 0.5 kt per year, a decrease of between 20 percent and 50 percent.

Planned Improvements

EPA is initiating research for data on SiC consumption by end-use for consideration in updating emissions estimates from SiC consumption and to account for emissions where they occur. This planned improvement is subject to data availability and will be implemented in the medium- to long-term.

EPA has not integrated aggregated facility-level GHGRP information to inform estimates of CO_2 and CH_4 from SiC production and consumption. The aggregated information (e.g., activity data and emissions) associated with silicon carbide did not meet criteria to shield underlying confidential business information (CBI) from public disclosure. EPA plans to examine the use of GHGRP silicon carbide emissions data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories. This planned improvement is ongoing and has not been incorporated into this Inventory report. This is a long-term planned improvement.

4.11 Titanium Dioxide Production (CRF Source Category 2B6)

Titanium dioxide (TiO_2) is manufactured using one of two processes: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related carbon dioxide (CO_2). Emissions from fuels consumed for energy purposes during the production of titanium dioxide are accounted for in the Energy chapter. The sulfate process does not use petroleum coke or other forms of carbon as a raw material and does not emit CO_2. The chloride process is based on the following chemical reactions and does emit CO_2:

$$2FeTiO_3 + 7Cl_2 + 3C \rightarrow 2TiCl_4 + 2FeCl_3 + 3CO_2$$

$$2TiCl_4 + 2O_2 \rightarrow 2TiO_2 + 4Cl_2$$

The carbon in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and $FeTiO_3$ (rutile ore) to form CO_2. Since 2004, all TiO_2 produced in the United States has been produced using the chloride process, and a special grade of “calcined” petroleum coke is manufactured specifically for this purpose.

The principal use of TiO_2 is as a white pigment in paint, lacquers, and varnishes. It is also used as a pigment in the manufacture of plastics, paper, and other products. In 2020, U.S. TiO_2 production totaled 1,000,000 metric tons (USGS 2021a). Five plants produced TiO_2 in the United States in 2020.

Emissions of CO_2 from titanium dioxide production in 2020 were estimated to be 1.3 MMT CO_2 Eq. (1,340 kt CO_2), which represents an increase of 12 percent since 1990 (see Table 4-40). Compared to 2019, emissions from titanium dioxide production decreased by 9 percent in 2020, due to a 9 percent decrease in production. Demand

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[38] The data were confirmed with Environment and Climate Change Canada.

for TiO_2 pigments decreased during the first half of 2020 due to restrictions implemented during the COVID-19 pandemic (USGS 2021a).

Table 4-40: CO_2 Emissions from Titanium Dioxide (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.2	1,195
2005	1.8	1,755
2016	1.7	1,662
2017	1.7	1,688
2018	1.5	1,541
2019	1.5	1,474
2020	1.3	1,340

Methodology and Time-Series Consistency

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual national TiO_2 production by chloride process-specific emission factors using a Tier 1 approach provided in *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

Equation 4-8: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions from Titanium Production (Equation 3.12)

$$E_{td} = EF_{td} \times Q_{td}$$

where,

E_{td} = CO_2 emissions from TiO_2 production, metric tons
EF_{td} = Emission factor (chloride process), metric ton CO_2/metric ton TiO_2
Q_{td} = Quantity of TiO_2 produced, metric tons

The petroleum coke portion of the total CO_2 process emissions from TiO_2 production is adjusted for within the Energy chapter as these fuels were consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (Section 3.1 Fossil Fuel Combustion) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Data were obtained for the total amount of TiO_2 produced each year. For years prior to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate process plant in the United States closed; therefore, 100 percent of production since 2004 used the chloride process (USGS 2005). An emission factor of 1.34 metric tons CO_2/metric ton TiO_2 was applied to the estimated chloride-process production (IPCC 2006). It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other carbon inputs.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines*. Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2017 (see Table 4-41) were obtained through the U.S. Geological Survey (USGS) *Minerals Yearbook: Titanium* (USGS 1991 through 2020). Production data for 2018 through 2019 were obtained from the USGS Minerals Yearbook: Titanium, advanced data release of the 2019 tables (USGS 2021b). Production data for 2020 were obtained from the *Minerals Commodity Summaries: Titanium and Titanium Dioxide* (USGS 2021a).[39] Data on the percentage of total TiO_2 production capacity that is chloride process were not available for 1990 through 1993, so data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate process plant closed in September 2001, the chloride process percentage for 2001 was estimated based on a discussion with Joseph Gambogi (Gambogi 2002). By 2002, only one sulfate process plant remained online in the United States, and this plant closed in 2004 (USGS 2005).

Table 4-41: Titanium Dioxide Production (kt)

Year	kt
1990	979
2005	1,310
2016	1,240
2017	1,260
2018	1,150
2019	1,100
2020	1,000

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

Each year, the USGS collects titanium industry data for titanium mineral and pigment production operations. If TiO_2 pigment plants do not respond, production from the operations is estimated based on prior year production levels and industry trends. Variability in response rates fluctuates from 67 to 100 percent of TiO_2 pigment plants over the time series.

Although some TiO_2 may be produced using graphite or other carbon inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated using petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

As of 2004, the last remaining sulfate-process plant in the United States closed. Since annual TiO_2 production was not reported by USGS by the type of production process used (chloride or sulfate) prior to 2004 and only the percentage of total production capacity by process was reported, the percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process. Finally, the emission factor was applied uniformly to all chloride-process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-42. Titanium dioxide consumption CO_2 emissions from 2020 were estimated to be between 1.2 and 1.5 MMT CO_2 Eq. at the 95 percent

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[39] EPA has not integrated aggregated facility-level GHGRP information for Titanium Dioxide production facilities (40 CFR Part 98 Subpart EE). The relevant aggregated information (activity data, emission factor) from these facilities did not meet criteria to shield underlying CBI from public disclosure.

confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.3 MMT CO_2 Eq.

Table 4-42: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.3	1.2	1.5	-13%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of the *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

EPA plans to examine the use of GHGRP titanium dioxide emissions and other data for possible use in emission estimates consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[40] This planned improvement is ongoing and has not been incorporated into this Inventory report. This is a long-term planned improvement.

4.12 Soda Ash Production (CRF Source Category 2B7)

Carbon dioxide (CO_2) is generated as a byproduct of calcining trona ore to produce soda ash and is eventually emitted into the atmosphere. In addition, CO_2 may also be released when soda ash is consumed. Emissions from soda ash consumption not associated with glass production are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4), and emissions from fuels consumed for energy purposes during the production and consumption of soda ash are accounted for in the Energy chapter.

Calcining involves placing crushed trona ore into a kiln to convert sodium bicarbonate into crude sodium carbonate that will later be filtered into pure soda ash. The emission of CO_2 during trona-based production is based on the following reaction:

$$2Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O(Trona) \rightarrow 3Na_2CO_3(Soda\ Ash) + 5H_2O + CO_2$$

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[40] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

Soda ash (sodium carbonate, Na_2CO_3) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. The largest use of soda ash is for glass manufacturing. Emissions from soda ash used in glass production are reported under Section 4.2, Glass Production (CRF Source Category 2A3). In addition, soda ash is used primarily to manufacture many sodium-based inorganic chemicals, including sodium bicarbonate, sodium chromates, sodium phosphates, and sodium silicates (USGS 2018b). Internationally, two types of soda ash are produced: natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash production. Trona is the principal ore from which natural soda ash is made.

The United States represents about one-fifth of total world soda ash output (USGS 2021a). Only two states produce natural soda ash: Wyoming and California. Of these two states, net emissions of CO_2 from soda ash production were only calculated for Wyoming, due to specifics regarding the production processes employed in the state.[41] Based on 2020 reported data, the estimated distribution of soda ash by end-use in 2020 (excluding glass production) was chemical production, 54 percent; other uses, 15 percent; soap and detergent manufacturing, 11 percent; wholesale distributors (e.g., for use in agriculture, water treatment, and grocery wholesale), 10 percent; flue gas desulfurization, 6 percent; water treatment, 2 percent; and pulp and paper production, 2 percent (USGS 2021b).[42]

U.S. natural soda ash is competitive in world markets because it is generally considered a better-quality raw material than synthetically produced soda ash, and the majority of the world output of soda ash is made synthetically. Although the United States continues to be a major supplier of soda ash, China surpassed the United States in soda ash production in 2003, becoming the world's leading producer.

In 2020, CO_2 emissions from the production of soda ash from trona ore were 1.5 MMT CO_2 Eq. (1,461 kt CO_2) (see Table 4-43). Total emissions from soda ash production in 2020 decreased by approximately 18 percent compared to emissions in 2019 primarily due to decreased global demand associated with the COVID-19 pandemic and have increased by approximately 2 percent from 1990 levels.

Other than the significant decrease observed in 2020, emissions have remained relatively constant over the time series with some fluctuations since 1990. In general, these fluctuations were related to the behavior of the export market and the U.S. economy. The U.S. soda ash industry had continued a trend of increased production and value through 2019 since experiencing a decline in domestic and export sales caused by adverse global economic conditions in 2009.

Table 4-43: CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and kt CO_2)

Year	MMT CO_2 Eq.	kt CO_2
1990	1.4	1,431
2005	1.7	1,655
2016	1.7	1,723
2017	1.8	1,753

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[41] In California, soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a byproduct, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted. A facility in a third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona ore in the state. For a brief time, sodium bicarbonate was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Prior to 2004, because the trona ore was mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

[42] Percentages may not add up to 100 percent due to independent rounding.

2018	1.7	1,714
2019	1.8	1,792
2020	1.5	1,461

Methodology and Time-Series Consistency

During the soda ash production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as byproducts of the calcination process. Carbon dioxide emissions from the calcination of trona ore can be estimated based on the chemical reaction shown above. Based on this formula, which is consistent with an IPCC Tier 1 approach, approximately 10.27 metric tons of trona ore are required to generate one metric ton of CO_2, or an emission factor of 0.0974 metric tons CO_2 per metric ton of trona ore (IPCC 2006). Thus, the 15.0 million metric tons of trona ore mined in 2020 for soda ash production (USGS 2021b) resulted in CO_2 emissions of approximately 1.5 MMT CO_2 Eq. (1,461 kt).

Once produced, most soda ash is consumed in chemical production, with minor amounts used in soap production, pulp and paper, flue gas desulfurization, and water treatment (excluding soda ash consumption for glass manufacturing). As soda ash is consumed for these purposes, additional CO_2 is usually emitted. Consistent with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, emissions from soda ash consumption in chemical production processes are reported under Section 4.4 Other Process Uses of Carbonates (CRF Category 2A4).

Data is not currently available for the quantity of trona used in soda ash production. Because trona ore produced is used primarily for soda ash production, EPA assumes that all trona produced was used in soda ash production. The activity data for trona ore production (see Table 4-44) for 1990 through 2020 were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook for Soda Ash* (1994 through 2015b) and USGS *Mineral Industry Surveys for Soda Ash* (USGS 2016 through 2017, 2018a, 2019, 2020, 2021b). Soda ash production[43] data were collected by the USGS from voluntary surveys of the U.S. soda ash industry. EPA will continue to analyze and assess opportunities to use facility-level data from EPA's GHGRP to improve the emission estimates for the Soda Ash Production source category consistent with IPCC[44] and UNFCCC guidelines.

Table 4-44: Trona Ore Used in Soda Ash Production (kt)

Year	Use[a]
1990	14,700
2005	17,000
2016	17,700
2017	18,000
2018	17,600
2019	18,400
2020	15,000

[a] Trona ore use is assumed to be equal to trona ore production.

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2020.

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[43] EPA has assessed the feasibility of using emissions information (including activity data) from EPA's GHGRP program. At this time, the aggregated information associated with production of soda ash did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

[44] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels because reliable and accurate data sources are available for the emission factor and activity data for trona-based soda ash production. One source of uncertainty is the purity of the trona ore used for manufacturing soda ash. The emission factor used for this estimate assumes the ore is 100 percent pure and likely overestimates the emissions from soda ash manufacture. The average water-soluble sodium carbonate-bicarbonate content for ore mined in Wyoming ranges from 85.5 to 93.8 percent (USGS 1995c).

EPA is aware of one facility producing soda ash from a liquid alkaline feedstock process, based on EPA's GHGRP. Soda ash production data was collected by the USGS from voluntary surveys. A survey request was sent to each of the five soda ash producers, all of which responded, representing 100 percent of the total production data (USGS 2020b).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-45. Soda ash production CO_2 emissions for 2020 were estimated to be between 1.3 and 1.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below and 8 percent above the emission estimate of 1.5 MMT CO_2 Eq.

Table 4-45: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Soda Ash Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production	CO_2	1.5	1.3	1.5	-9%	+8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

4.13 Petrochemical Production (CRF Source Category 2B8)

The production of some petrochemicals results in the release of carbon dioxide (CO_2) and methane (CH_4) emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. Carbon dioxide emissions from the production of acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, and methanol, and CH_4 emissions from the production of methanol and acrylonitrile are presented here and reported under IPCC Source Category 2B8. The petrochemical industry uses primary fossil fuels (i.e., natural gas, coal, petroleum, etc.) for non-fuel purposes in the production of carbon black and other petrochemicals. Emissions from fuels and feedstocks transferred out of the system for use in energy purposes (e.g., indirect or direct process heat or steam production) are currently accounted for in the Energy sector. The allocation and reporting of emissions from feedstocks transferred out of the system for use in energy purposes to the Energy chapter is consistent with the *2006 IPCC Guidelines*.

Worldwide, more than 90 percent of acrylonitrile (vinyl cyanide, C_3H_3N) is made by way of direct ammoxidation of propylene with ammonia (NH_3) and oxygen over a catalyst. This process is referred to as the SOHIO process, named after the Standard Oil Company of Ohio (SOHIO) (IPCC 2006). The primary use of acrylonitrile is as the raw material for the manufacture of acrylic and modacrylic fibers. Other major uses include the production of plastics (acrylonitrile-butadiene-styrene [ABS] and styrene-acrylonitrile [SAN]), nitrile rubbers, nitrile barrier resins, adiponitrile, and acrylamide. All U.S. acrylonitrile facilities use the SOHIO process (AN 2014). The SOHIO process involves a fluidized bed reaction of chemical-grade propylene, ammonia, and oxygen over a catalyst. The process produces acrylonitrile as its primary product, and the process yield depends on the type of catalyst used and the process configuration. The ammoxidation process produces byproduct CO_2, carbon monoxide (CO), and water from the direct oxidation of the propylene feedstock and produces other hydrocarbons from side reactions.

Carbon black is a black powder generated by the incomplete combustion of an aromatic petroleum- or coal-based feedstock at a high temperature. Most carbon black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. The other major use of carbon black is as a pigment. The predominant process used in the United States to produce carbon black is the furnace black (or oil furnace) process. In the furnace black process, carbon black oil (a heavy aromatic liquid) is continuously injected into the combustion zone of a natural gas-fired furnace. Furnace heat is provided by the natural gas and a portion of the carbon black feedstock; the remaining portion of the carbon black feedstock is pyrolyzed to carbon black. The resultant CO_2 and uncombusted CH_4 emissions are released from thermal incinerators used as control devices, process dryers, and equipment leaks. Three facilities in the United States use other types of carbon black processes. Specifically, one facility produces carbon black by the thermal cracking of acetylene-containing feedstocks (i.e., acetylene black process), a second facility produces carbon black by the thermal cracking of other hydrocarbons (i.e., thermal black process), and a third facility produces carbon black by the open burning of carbon black feedstock (i.e., lamp black process) (EPA 2000).

Ethylene (C_2H_4) is consumed in the production processes of the plastics industry including polymers such as high, low, and linear low density polyethylene (HDPE, LDPE, LLDPE); polyvinyl chloride (PVC); ethylene dichloride; ethylene oxide; and ethylbenzene. Virtually all ethylene is produced from steam cracking of ethane, propane, butane, naphtha, gas oil, and other feedstocks. The representative chemical equation for steam cracking of ethane to ethylene is shown below:

$$C_2H_6 \rightarrow C_2H_4 + H_2$$

Small amounts of CH_4 are also generated from the steam cracking process. In addition, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene dichloride ($C_2H_4Cl_2$) is used to produce vinyl chloride monomer, which is the precursor to polyvinyl chloride (PVC). Ethylene dichloride was also used as a fuel additive until 1996 when leaded gasoline was phased out. Ethylene dichloride is produced from ethylene by either direct chlorination, oxychlorination, or a combination of the two processes (i.e., the “balanced process”); most U.S. facilities use the balanced process. The direct chlorination and oxychlorination reactions are shown below:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \text{ (direct chlorination)}$$

$$C_2H_4 + \tfrac{1}{2}O_2 + 2HCl \rightarrow C_2H_4Cl_2 + 2H_2O \text{ (oxychlorination)}$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \text{ (direct oxidation of ethylene during oxychlorination)}$$

In addition to the byproduct CO_2 produced from the direction oxidation of the ethylene feedstock, CO_2 and CH_4 emissions are also generated from combustion units.

Ethylene oxide (C_2H_4O) is used in the manufacture of glycols, glycol ethers, alcohols, and amines. Approximately 70 percent of ethylene oxide produced worldwide is used in the manufacture of glycols, including monoethylene glycol. Ethylene oxide is produced by reacting ethylene with oxygen over a catalyst. The oxygen may be supplied to the process through either an air (air process) or a pure oxygen stream (oxygen process). The byproduct CO_2 from the direct oxidation of the ethylene feedstock is removed from the process vent stream using a recycled carbonate solution, and the recovered CO_2 may be vented to the atmosphere or recovered for further utilization in other sectors, such as food production (IPCC 2006). The combined ethylene oxide reaction and byproduct CO_2 reaction is exothermic and generates heat, which is recovered to produce steam for the process. The ethylene oxide process also produces other liquid and off-gas byproducts (e.g., ethane that may be burned for energy recovery within the process. Almost all facilities, except one in Texas, use the oxygen process to manufacture ethylene oxide (EPA 2008).

Methanol (CH_3OH) is a chemical feedstock most often converted into formaldehyde, acetic acid and olefins. It is also an alternative transportation fuel, as well as an additive used by municipal wastewater treatment facilities in the denitrification of wastewater. Methanol is most commonly synthesized from a synthesis gas (i.e., “syngas” – a mixture containing H_2, CO, and CO_2) using a heterogeneous catalyst. There are a number of process techniques that can be used to produce syngas. Worldwide, steam reforming of natural gas is the most common method; most methanol producers in the United States also use steam reforming of natural gas to produce syngas. Other syngas production processes in the United States include partial oxidation of natural gas and coal gasification.

Emissions of CO_2 and CH_4 from petrochemical production in 2020 were 30.0 MMT CO_2 Eq. (30,011 kt CO_2) and 0.3 MMT CO_2 Eq. (13 kt CH_4), respectively (see Table 4-46 and Table 4-47). Carbon dioxide emissions from petrochemical production are driven primarily from ethylene production, while CH_4 emissions are almost entirely from methanol production. Since 1990, total CO_2 emissions from petrochemical production increased by 39 percent, and CH4 emissions increased by 43 percent. Emissions of CO_2 in 2020 are 7 percent below the peak in 1999, and CH_4 emissions in 2020 are 9 percent below the peak in 1997. Compared to 2019, CO_2 emissions decreased 2 percent in 2020, and CH_4 emissions decreased 5 percent. This decrease in emissions is due in part to lower production as a result of the COVID-19 pandemic reducing demand and also a strong hurricane season that temporarily shut down operations in Texas and Louisiana in 2020.

Table 4-46: CO_2 and CH_4 Emissions from Petrochemical Production (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
CO_2	**21.6**	**27.4**	**28.1**	**28.9**	**29.3**	**30.7**	**30.0**
Carbon Black	3.4	4.3	3.2	3.3	3.4	3.3	2.6
Ethylene	13.1	19.0	19.6	20.0	19.4	20.7	20.7
Ethylene Dichloride	0.3	0.5	0.4	0.4	0.4	0.5	0.5
Ethylene Oxide	1.1	1.5	1.1	1.3	1.3	1.4	1.7
Acrylonitrile	1.2	1.3	1.0	1.0	1.3	1.0	0.9
Methanol	2.5	0.8	2.8	2.9	3.5	3.8	3.6
CH_4	**0.2**	**0.1**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**
Acrylonitrile	+	+	+	+	+	+	+
Methanol	0.2	0.1	0.2	0.2	0.3	0.3	0.3
Total	**21.8**	**27.5**	**28.4**	**29.1**	**29.6**	**31.0**	**30.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 4-47: CO_2 and CH_4 Emissions from Petrochemical Production (kt)

Year	1990	2005	2016	2017	2018	2019	2020
CO_2	**21,611**	**27,383**	**28,110**	**28,890**	**29,314**	**30,702**	**30,011**
Carbon Black	3,381	4,269	3,160	3,310	3,440	3,300	2,610
Ethylene	13,126	19,024	19,600	20,000	19,400	20,700	20,700
Ethylene Dichloride	254	455	447	412	440	503	456
Ethylene Oxide	1,123	1,489	1,100	1,250	1,300	1,370	1,680
Acrylonitrile	1,214	1,325	955	1,040	1,250	990	930
Methanol	2,513	821	2,848	2,878	3,484	3,839	3,635
CH_4	**9**	**3**	**10**	**10**	**12**	**13**	**13**

Acrylonitrile	+		+		+	+	+	+	+
Methanol	9		3		10	10	12	13	12

+ Does not exceed 0.5 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 were calculated using the estimation methods provided by the *2006 IPCC Guidelines* and country-specific methods from EPA's GHGRP. The *2006 IPCC Guidelines* Tier 1 method was used to estimate CO_2 and CH_4 emissions from production of acrylonitrile and methanol,[45] and a country-specific approach similar to the IPCC Tier 2 method was used to estimate CO_2 emissions from production of carbon black, ethylene oxide, ethylene, and ethylene dichloride. The Tier 2 method for petrochemicals is a total feedstock carbon (C) mass balance method used to estimate total CO_2 emissions, but it is not applicable for estimating CH_4 emissions.

As noted in the *2006 IPCC Guidelines*, the total feedstock C mass balance method (Tier 2) is based on the assumption that all of the C input to the process is converted either into primary and secondary products or into CO_2. Further, the guideline states that while the total C mass balance method estimates total C emissions from the process, it does not directly provide an estimate of the amount of the total C emissions emitted as CO_2, CH_4, or non-CH_4 volatile organic compounds (NMVOCs). This method accounts for all the C as CO_2, including CH_4.

Note, a small subset of facilities reporting under EPA's GHGRP use Continuous Emission Monitoring Systems (CEMS) to monitor CO_2 emissions from process vents and/or stacks from stationary combustion units, these facilities are required to also report CO_2, CH_4 and N_2O emissions from combustion of process off-gas in flares. The CO_2 from flares are included in aggregated CO_2 results. Preliminary analysis of aggregated annual reports shows that flared CH_4 and N_2O emissions are less than 500 kt CO_2 Eq./year. EPA's GHGRP team is still reviewing these data across reported years, and EPA plans to address this more completely in future reports.

Carbon Black, Ethylene, Ethylene Dichloride, and Ethylene Oxide

2010 through 2020

Carbon dioxide emissions and national production were aggregated directly from EPA's GHGRP dataset for 2010 through 2020 (EPA 2021). In 2020, data reported to the GHGRP included CO_2 emissions of 2,610,000 metric tons from carbon black production; 20,700,000 metric tons of CO_2 from ethylene production; 456,000 metric tons of CO_2 from ethylene dichloride production; and 1,680,000 metric tons of CO_2 from ethylene oxide production. These emissions reflect application of a country-specific approach similar to the IPCC Tier 2 method and were used to estimate CO_2 emissions from the production of carbon black, ethylene, ethylene dichloride, and ethylene oxide.

Since 2010, EPA's GHGRP, under Subpart X, requires all domestic producers of petrochemicals to report annual emissions and supplemental emissions information (e.g., production data, etc.) to facilitate verification of reported emissions. Under EPA's GHGRP, most petrochemical production facilities are required to use either a mass balance approach or CEMS to measure and report emissions for each petrochemical process unit to estimate facility-level process CO_2 emissions; ethylene production facilities also have a third option. The mass balance method is used by most facilities[46] and assumes that all the carbon input is converted into primary and secondary products, byproducts, or is emitted to the atmosphere as CO_2. To apply the mass balance, facilities must measure the volume or mass of each gaseous and liquid feedstock and product, mass rate of each solid feedstock and product, and carbon content of each feedstock and product for each process unit and sum for their facility. To apply the

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[45] EPA has not integrated aggregated facility-level GHGRP information for acrylonitrile and methanol production. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

[46] A few facilities producing ethylene dichloride, ethylene, and methanol used CO_2 CEMS; those CO_2 emissions have been included in the aggregated GHGRP emissions presented here.

optional combustion methodology, ethylene production facilities must measure the quantity, carbon content, and molecular weight of the fuel to a stationary combustion unit when that fuel includes any ethylene process off-gas. These data are used to calculate the total CO_2 emissions from the combustion unit. The facility must also estimate the fraction of the emissions that is attributable to burning the ethylene process off-gas portion of the fuel. This fraction is multiplied by the total emissions to estimate the emissions from ethylene production. The QA/QC and Verification section below has a discussion of non-CO_2 emissions from ethylene production facilities.

All non-energy uses of residual fuel and some non-energy uses of "other oil" are assumed to be used in the production of carbon black; therefore, consumption of these fuels is adjusted for within the Energy chapter to avoid double-counting of emissions from fuel used in the carbon black production presented here within IPPU sector. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (IPCC Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

1990 through 2009

Prior to 2010, for each of these 4 types of petrochemical processes, an average national CO_2 emission factor was calculated based on the GHGRP data and applied to production for earlier years in the time series (i.e., 1990 through 2009) to estimate CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production. For carbon black, ethylene, ethylene dichloride, and ethylene oxide carbon dioxide emission factors were derived from EPA's GHGRP data by dividing annual CO_2 emissions for petrochemical type "i" with annual production for petrochemical type "i" and then averaging the derived emission factors obtained for each calendar year 2010 through 2013 (EPA 2019). The years 2010 through 2013 were used in the development of carbon dioxide emission factors as these years are more representative of operations in 1990 through 2009 for these facilities. The average emission factors for each petrochemical type were applied across all prior years because petrochemical production processes in the United States have not changed significantly since 1990, though some operational efficiencies have been implemented at facilities over the time series.

The average country-specific CO_2 emission factors that were calculated from the GHGRP data are as follows:

- 2.59 metric tons CO_2/metric ton carbon black produced
- 0.79 metric tons CO_2/metric ton ethylene produced
- 0.040 metric tons CO_2/metric ton ethylene dichloride produced
- 0.46 metric tons CO_2/metric ton ethylene oxide produced

Annual production data for carbon black for 1990 through 2009 were obtained from the International Carbon Black Association (Johnson 2003 and 2005 through 2010). Annual production data for ethylene, ethylene dichloride, and ethylene oxide for 1990 through 2009 were obtained from the American Chemistry Council's (ACC's) *Business of Chemistry* (ACC 2021).

Acrylonitrile

Carbon dioxide and methane emissions from acrylonitrile production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Annual acrylonitrile production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2019. Emission factors used to estimate acrylonitrile production emissions are as follows:

- 0.18 kg CH_4/metric ton acrylonitrile produced
- 1.00 metric tons CO_2/metric ton acrylonitrile produced

Annual acrylonitrile production data for 1990 through 2020 were obtained from ACC's *Business of Chemistry* (ACC 2021). EPA is not able to apply the aggregated facility-level GHGRP information for acrylonitrile production needed for a Tier 2 approach. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Methanol

Carbon dioxide and methane emissions from methanol production were estimated using the Tier 1 method in the *2006 IPCC Guidelines*. Annual methanol production data were used with IPCC default Tier 1 CO_2 and CH_4 emission factors to estimate emissions for 1990 through 2020. Emission factors used to estimate methanol production emissions are as follows:

- 2.3 kg CH_4/metric ton methanol produced
- 0.67 metric tons CO_2/metric ton methanol produced

Annual methanol production data for 1990 through 2020 were obtained from the ACC's *Business of Chemistry* (ACC 2021). EPA is not able to apply the aggregated facility-level GHGRP information for methanol production needed for a Tier 2 approach. The aggregated information associated with production of these petrochemicals did not meet criteria to shield underlying CBI from public disclosure.

Table 4-48: Production of Selected Petrochemicals (kt)

Chemical	1990	2005	2016	2017	2018	2019	2020
Carbon Black	1,310	1,650	1,190	1,240	1,280	1,210	990
Ethylene	16,500	24,000	26,600	27,800	30,500	32,400	33,500
Ethylene Dichloride	6,280	11,300	11,700	12,400	12,500	12,600	11,900
Ethylene Oxide	2,430	3,220	3,210	3,350	3,310	3,800	4,680
Acrylonitrile	1,214	1,325	955	1,040	1,250	990	930
Methanol	3,750	1,225	4,250	4,295	5,200	5,730	5,425

As noted earlier in the introduction section of the Petrochemical Production section, the allocation and reporting of emissions from both fuels and feedstocks transferred out of the system for use in energy purposes to the Energy chapter differs slightly from the *2006 IPCC Guidelines*. According to the *2006 IPCC Guidelines*, emissions from fuel combustion from petrochemical production should be allocated to this source category within the IPPU chapter. Due to national circumstances, EIA data on primary fuel for feedstock use within the energy balance are presented by commodity only, with no resolution on data by industry sector (i.e., petrochemical production). In addition, under EPA's GHGRP, reporting facilities began reporting in 2014 on annual feedstock quantities for mass balance and CEMS methodologies (79 FR 63794), as well as the annual average carbon content of each feedstock (and molecular weight for gaseous feedstocks) for the mass balance methodology beginning in reporting year 2017 (81 FR 89260).[47] The United States is currently unable to report non-energy fuel use from petrochemical production under the IPPU chapter due to CBI issues. Therefore, consistent with *2006 IPCC Guidelines*, fuel consumption data reported by EIA are modified to account for these overlaps to avoid double-counting. More information on the non-energy use of fossil fuel feedstocks for petrochemical production can be found in Annex 2.3.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for ethylene production, ethylene dichloride production, and ethylene oxide production spliced activity data from two different sources: ACC for 1990 through 2009 and GHGRP for 2010 through 2020. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data sets for years where there was overlap. For ethylene production, the data sets were determined to be consistent, and adjustments were not needed. For ethylene dichloride production and ethylene oxide production, the data sets were determined to be inconsistent. The GHGRP data includes production of ethylene dichloride and ethylene oxide as intermediates while it is unclear if the ACC data does; therefore, no adjustments were made to the ethylene dichloride and ethylene oxide activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent. The methodology for carbon black production also spliced activity data from two different sources: ICBA for 1990

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[47] See https://www.epa.gov/ghgreporting/historical-rulemakings.

through 2009 and GHGRP for 2010 through 2020. The overlap technique was applied to these data for 2010 and 2011. The data sets were determined to be consistent, and adjustments were not needed.

Uncertainty

The CO_2 and CH_4 emission factors used for methanol and acrylonitrile production are based on a limited number of studies. Using plant-specific factors instead of default or average factors could increase the accuracy of the emission estimates; however, such data were not available for the current Inventory report. For methanol, EPA assigned an uncertainty range of ±30 percent for the CO_2 emission factor and -80 percent to +30 percent for the CH_4 emission factor, consistent with the ranges in Table 3.27 of the *2006 IPCC Guidelines*. For acrylonitrile, EPA assigned an uncertainty range of ±60 percent for the CO_2 emission factor and ±10 percent for the CH_4 emission factor, consistent with the ranges in Table 3.27 of the *2006 IPCC Guidelines.* The results of the quantitative uncertainty analysis for the CO_2 emissions from carbon black production, ethylene, ethylene dichloride, and ethylene oxide are based on reported GHGRP data. Refer to the Methodology section for more details on how these emissions were calculated and reported to EPA's GHGRP. EPA assigned CO_2 emissions from carbon black, ethylene, ethylene dichloride, and ethylene oxide production an uncertainty range of ±5 percent, consistent with the ranges in Table 3.27 of the *2006 IPCC Guidelines.* In the absence of other data, these values have been assessed as reasonable. There is some uncertainty in the applicability of the average emission factors for each petrochemical type across all prior years. While petrochemical production processes in the United States have not changed significantly since 1990, some operational efficiencies have been implemented at facilities over the time series.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-49. Petrochemical production CO_2 emissions from 2020 were estimated to be between 28.4 and 31.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 6 percent above the emission estimate of 30.0 MMT CO_2 Eq. Petrochemical production CH_4 emissions from 2020 were estimated to be between 0.11 and 0.39 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 57 percent below to 47 percent above the emission estimate of 0.3 MMT CO_2 Eq.

Table 4-49: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Petrochemical Production and CO_2 Emissions from Petrochemical Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO_2	30.0	28.4	31.7	-5%	+6%
Petrochemical Production	CH_4	0.3	0.11	0.39	-57%	+47%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For Petrochemical Production, QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan, as described in the QA/QC and Verification Procedures section of the IPPU chapter and Annex 8. Source-specific quality control measures for this category included the QA/QC requirements and verification procedures of EPA's GHGRP. More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to petrochemical facilities can be found under Subpart X (Petrochemical Production) of the regulation (40 CFR Part

98).[48] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[49] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. EPA also conducts QA checks of GHGRP reported production data by petrochemical type against external datasets.

For ethylene, ethylene dichloride, and ethylene oxide, it is possible to compare CO_2 emissions calculated using the GHGRP data to the CO_2 emissions that would have been calculated using the Tier 1 approach if GHGRP data were not available. For ethylene, the GHGRP emissions were within 5 percent of the emissions calculated using the Tier 1 approach prior to 2018; in 2018 through 2020, the GHGRP emissions have been about 20 percent lower than what would be calculated using the Tier 1 approach. For ethylene dichloride, the GHGRP emissions are typically higher than the Tier 1 emissions by up to 25 percent. For ethylene oxide, GHGRP emissions vary from 17 percent less than the Tier 1 emissions to 20 percent more than the Tier 1 emissions, depending on the year.

EPA's GHGRP mandates that all petrochemical production facilities report their annual emissions of CO_2, CH_4, and N_2O from each of their petrochemical production processes. Source-specific quality control measures for the Petrochemical Production category included the QA/QC requirements and verification procedures of EPA's GHGRP. The QA/QC requirements differ depending on the calculation methodology used.

As part of a planned improvement effort, EPA has assessed the potential of using GHGRP data to estimate CH_4 emissions from ethylene production. As discussed in the Methodology section above, CO_2 emissions from ethylene production in this chapter are based on data reported under the GHGRP, and these emissions are calculated using a Tier 2 approach that assumes all of the carbon in the fuel (i.e., ethylene process off-gas) is converted to CO_2. Ethylene production facilities also calculate and report CH_4 emissions under the GHGRP when they use the optional combustion methodology. The facilities calculate CH_4 emissions from each combustion unit that burns off-gas from an ethylene production process unit using a Tier 1 approach based on the total quantity of fuel burned, a default higher heating value, and a default emission factor. Because multiple other types of fuel in addition to the ethylene process unit off-gas may be burned in these combustion units, the facilities also report an estimate of the fraction of emissions that is due to burning the ethylene process off-gas component of the total fuel. Multiplying the total emissions by the estimated fraction provides an estimate of the CH_4 emissions from the ethylene production process unit. These ethylene production facilities also calculate CH_4 emissions from flares that burn process vent emissions from ethylene processes. The emissions are calculated using either a Tier 2 approach based on measured gas volumes and measured carbon content or higher heating value, or a Tier 1 approach based on the measured gas flow and a default emission factor. Nearly all ethylene production facilities use the optional combustion methodology under the GHGRP, and the sum of reported CH_4 emissions from combustion in stationary combustion units and flares at all of these facilities is on the same order of magnitude as the combined CH_4 emissions presented in this chapter from methanol and acrylonitrile production. The CH_4 emissions from ethylene production under the GHGRP have not been included in this chapter because this approach double counts carbon (i.e., all of the carbon in the CH_4 emissions is also included in the CO_2 emissions from the ethylene process units). EPA continues to assess the GHGRP data for ways to better disaggregate the data and incorporate it into the inventory.

These facilities are also required to report emissions of N_2O from combustion of ethylene process off-gas in both stationary combustion units and flares. Facilities using CEMS (consistent with a Tier 3 approach) are also required to report emissions of CH_4 and N_2O from combustion of petrochemical process-off gases in flares. Preliminary analysis of the aggregated reported CH_4 and N_2O emissions from facilities using CEMS and N_2O emissions from facilities using the optional combustion methodology suggests that these annual emissions are less than 500 kt/yr,

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[48] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[49] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

which is not significant enough to prioritize for inclusion in the report at this time. Pending resources and significance, EPA may include these N_2O emissions in future reports to enhance completeness.

Future QC efforts to validate the use of Tier 1 default emission factors and report on the comparison of Tier 1 emission estimates and GHGRP data are described below in the Planned Improvements section.

Recalculations Discussion

The acrylonitrile production quantity for 2019 was updated with the revised value in ACC's Business of Chemistry (ACC 2021). This change resulted in less than a 0.3 percent (90 kt) decrease in total petrochemical emissions for 2019, compared to the previous Inventory.

Emissions from ethylene production in 2016 and emissions from carbon black production in 2017 were updated and reduced slightly to be consistent with updated GHGRP data (EPA 2021). These changes resulted in a 0.7 percent (200 kt) decrease in total emissions from petrochemical production for 2016 and a 0.07 percent (20 kt) decrease in total emissions from petrochemical production for 2017, compared to the previous Inventory.

Planned Improvements

Improvements include completing category-specific QC of activity data and emission factors, along with further assessment of CH_4 and N_2O emissions to enhance completeness in reporting of emissions from U.S. petrochemical production, pending resources, significance and time-series consistency considerations. For example, EPA is planning additional assessment of ways to use CH_4 data from the GHGRP in the Inventory. One possible approach EPA is assessing would be to adjust the CO_2 emissions from the GHGRP downward by subtracting the carbon that is also included in the reported CH_4 emissions, per the discussion in the Petrochemical Production QA/QC and Verification section, above. As of this current report, timing and resources have not allowed EPA to complete this analysis of activity data, emissions, and emission factors and remains a priority improvement within the IPPU chapter.

Pending resources, a secondary potential improvement for this source category would focus on continuing to analyze the fuel and feedstock data from EPA's GHGRP to better disaggregate energy-related emissions and allocate them more accurately between the Energy and IPPU sectors of the Inventory. It is important to ensure no double counting of emissions between fuel combustion, non-energy use of fuels, and industrial process emissions. For petrochemical feedstock production, EPA review of the categories suggests this is not a significant issue since the non-energy use industrial release data includes different categories of sources and sectors than those included in the IPPU emissions category for petrochemicals. As noted previously in the methodology section, data integration is not available at this time because feedstock data from the EIA used to estimate non-energy uses of fuels are aggregated by fuel type, rather than disaggregated by both fuel type and particular industries. Also, GHGRP-reported data on quantities of fuel consumed as feedstocks by petrochemical producers are unable to be used due to the data failing GHGRP CBI aggregation criteria. EPA will continue to look for ways to incorporate this data into future Inventories to will allow for easier data integration between the non-energy uses of fuels category and the petrochemicals category presented in this chapter. This planned improvement is still under development and has not been completed to report on progress in this current Inventory.

EPA plans to review USGS data to improve use of activity data to estimate emissions, consistent with the methodological decision trees in *2006 IPCC Guidelines*. EPA also plans to review GHGRP emissions data for possible use in estimates, consistent with both Volume 1, Chapter 6 of the *2006 IPCC Guidelines* and the latest IPCC guidance on the use of facility-level data in national inventories.[50] This planned improvement is ongoing and has not been incorporated into this Inventory report. This is a medium-term planned improvement and expected to be completed by the next (i.e., 2023) Inventory submission.

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[50] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

4.14 HCFC-22 Production (CRF Source Category 2B9a)

Trifluoromethane (HFC-23 or CHF_3) is generated as a byproduct during the manufacture of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Between 2000 and 2007, U.S. production fluctuated but generally remained above 1990 levels. In 2008 and 2009, U.S. production declined markedly and has remained near 2009 levels since. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses was phased out in 2020 under the U.S. Clean Air Act.[51] Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform ($CHCl_3$) and hydrogen fluoride (HF) in the presence of a catalyst, $SbCl_5$. The reaction of the catalyst and HF produces $SbCl_xF_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 ($CHCl_2F$), HCFC-22 ($CHClF_2$), HFC-23 (CHF_3), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful byproduct, and the HF is removed. Once separated from HCFC-22, the HFC-23 may be released to the atmosphere, recaptured for use in a limited number of applications, or destroyed.

Two facilities produced HCFC-22 in the United States in 2020. Emissions of HFC-23 from this activity in 2020 were estimated to be 2.1 MMT CO_2 Eq. (0.1 kt) (see Table 4-50). This quantity represents a 43 percent decrease from 2019 emissions and a 95 percent decrease from 1990 emissions. The decrease from 1990 emissions was caused primarily by changes in the HFC-23 emission rate (kg HFC-23 emitted/kg HCFC-22 produced). The decrease from 2019 emissions was caused by both a decrease in the HFC-23 emission rate at one plant and a decrease in the total quantity of HCFC-22 produced. The long-term decrease in the emission rate is primarily attributable to six factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990; (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22; (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated; (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale; (e) another plant began destroying HFC-23; and (f) the same plant, whose emission rate was higher than that of the other two plants, ceased production of HCFC-22 in 2013.

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[51] As construed, interpreted, and applied in the terms and conditions of the Montreal Protocol on Substances that Deplete the Ozone Layer [42 U.S.C. §7671m(b), CAA §614].

Table 4-50: HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and kt HFC-23)

Year	MMT CO_2 Eq.	kt HFC-23
1990	46.1	3
2005	20.0	1
2016	2.8	0.2
2017	5.2	0.3
2018	3.3	0.2
2019	3.7	0.3
2020	2.1	0.1

Methodology and Time-Series Consistency

To estimate HFC-23 emissions for five of the eight HCFC-22 plants that have operated in the United States since 1990, methods comparable to the Tier 3 methods in the *2006 IPCC Guidelines* (IPCC 2006) were used throughout the time series. Emissions for 2010 through 2020 were obtained through reports submitted by U.S. HCFC-22 production facilities to EPA's Greenhouse Gas Reporting Program (GHGRP). EPA's GHGRP mandates that all HCFC-22 production facilities report their annual emissions of HFC-23 from HCFC-22 production processes and HFC-23 destruction processes. Previously, data were obtained by EPA through collaboration with an industry association that received voluntarily reported HCFC-22 production and HFC-23 emissions annually from all U.S. HCFC-22 producers from 1990 through 2009. These emissions were aggregated and reported to EPA on an annual basis.

For the other three plants, the last of which closed in 1993, methods comparable to the Tier 1 method in the *2006 IPCC Guidelines* were used. Emissions from these three plants have been calculated using the recommended emission factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure (or, for the plants that have since closed, measured) concentrations of HFC-23 as well as mass flow rates of process streams to estimate their generation of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. One plant that releases a small fraction of its byproduct HFC-23 periodically measures HFC-23 concentrations at process vents using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

To estimate 1990 through 2009 emissions, reports from an industry association were used that aggregated HCFC-22 production and HFC-23 emissions from all U.S. HCFC-22 producers and reported them to EPA (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, and 2010). To estimate 2010 through 2020 emissions, facility-level data (including both HCFC-22 production and HFC-23 emissions) reported through EPA's GHGRP were analyzed. In 1997 and 2008, comprehensive reviews of plant-level estimates of HFC-23 emissions and HCFC-22 production were performed (RTI 1997; RTI 2008). The 1997 and 2008 reviews enabled U.S. totals to be reviewed, updated, and where necessary, corrected, and also for plant-level uncertainty analyses (Monte-Carlo simulations) to be performed for 1990, 1995, 2000, 2005, and 2006. Estimates of annual U.S. HCFC-22 production are presented in Table 4-51.

Table 4-51: HCFC-22 Production (kt)

Year	kt
1990	139
2005	156
2012	96
2013-2020	C

C (CBI)

Note: HCFC-22 production in 2013 through 2020 is considered Confidential Business Information (CBI) as there were only two producers of HCFC-22 in those years.

Uncertainty

The uncertainty analysis presented in this section was based on a plant-level Monte Carlo Stochastic Simulation for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates. The simulation for 2006 yielded a 95-percent confidence interval for U.S. emissions of 6.8 percent below to 9.6 percent above the reported total.

The relative errors yielded by the Monte Carlo Stochastic Simulation for 2006 were applied to the U.S. emission estimate for 2020. The resulting estimates of absolute uncertainty are likely to be reasonably accurate because (1) the methods used by the two remaining plants to estimate their emissions are not believed to have changed significantly since 2006, and (2) although the distribution of emissions among the plants has changed between 2006 and 2020 (because one plant has closed), the plant that currently accounts for most emissions had a relative uncertainty in its 2006 (as well as 2005) emissions estimate that was similar to the relative uncertainty for total U.S. emissions. Thus, the closure of one plant is not likely to have a large impact on the uncertainty of the national emission estimate.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-52. HFC-23 emissions from HCFC-22 production were estimated to be between 2.0 and 2.3 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 2.1 MMT CO_2 Eq.

Table 4-52: Approach 2 Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	2.1	2.0	2.3	-7%	+10%

[a] Range of emissions reflects a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). Under the GHGRP, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[52] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

The GHGRP also requires source-specific quality control measures for the HCFC-22 Production category. Under EPA's GHGRP, HCFC-22 producers are required to (1) measure concentrations of HFC-23 and HCFC-22 in the product stream at least weekly using equipment and methods (e.g., gas chromatography) with an accuracy and precision of 5 percent or better at the concentrations of the process samples, (2) measure mass flows of HFC-23 and HCFC-22 at least weekly using measurement devices (e.g., flowmeters) with an accuracy and precision of 1 percent of full scale or better, (3) calibrate mass measurement devices at the frequency recommended by the manufacturer using traceable standards and suitable methods published by a consensus standards organization, (4) calibrate gas chromatographs at least monthly through analysis of certified standards, and (5) document these calibrations.

Recalculations

The emissions estimate for 2011 was revised to exclude HFC-23 emissions from one plant that did not produce HCFC-22. This revision resulted in a decrease in 2011 emissions of 459 kg HFC-23, about 0.07 percent of the previous estimate.

4.15 Carbon Dioxide Consumption (CRF Source Category 2B10)

Carbon dioxide (CO_2) is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected underground to enable additional petroleum to be produced. For the purposes of this analysis, CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. A further discussion of CO_2 used in EOR is described in the Energy chapter in Box 3-6 titled "Carbon Dioxide Transport, Injection, and Geological Storage" and is not included in this section.

Carbon dioxide is produced from naturally-occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component.

In 2020, the amount of CO_2 produced and captured for commercial applications and subsequently emitted to the atmosphere was 5.0 MMT CO_2 Eq. (4,970 kt) (see Table 4-53). This is a 2 percent increase (100 kt) from 2019 levels and is an increase of approximately 238 percent since 1990.

Table 4-53: CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,472

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[52] EPA (2015). Greenhouse Gas Reporting Program Report Verification. Available online at: https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Year	MMT CO_2 Eq.	kt
2005	1.4	1,375
2016	4.6	4,640
2017	4.6	4,580
2018	4.1	4,130
2019	4.9	4,870
2020	5.0	4,970

Methodology and Time-Series Consistency

Carbon dioxide emission estimates for 1990 through 2020 were based on the quantity of CO_2 extracted and transferred for industrial applications (i.e., non-EOR end-uses). Some of the CO_2 produced by these facilities is used for EOR, and some is used in other commercial applications (e.g., chemical manufacturing, food production). It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

2010 through 2020

For 2010 through 2020, data from EPA's GHGRP (Subpart PP) were aggregated from facility-level reports to develop a national-level estimate for use in the Inventory (EPA 2021). Facilities report CO_2 extracted or produced from natural reservoirs and industrial sites, and CO_2 captured from energy and industrial processes and transferred to various end-use applications to EPA's GHGRP. This analysis includes only reported CO_2 transferred to food and beverage end-uses. EPA is continuing to analyze and assess integration of CO_2 transferred to other end-uses to enhance the completeness of estimates under this source category. Other end-uses include industrial applications, such as metal fabrication. EPA is analyzing the information reported to ensure that other end-use data excludes non-emissive applications and publication will not reveal CBI. Reporters subject to EPA's GHGRP Subpart PP are also required to report the quantity of CO_2 that is imported and/or exported. Currently, these data are not publicly available through the GHGRP due to data confidentiality reasons and hence are excluded from this analysis.

Facilities subject to Subpart PP of EPA's GHGRP are required to measure CO_2 extracted or produced. More details on the calculation and monitoring methods applicable to extraction and production facilities can be found under Subpart PP: Suppliers of Carbon Dioxide of the regulation, Part 98.[53] The number of facilities that reported data to EPA's GHGRP Subpart PP (Suppliers of Carbon Dioxide) for 2010 through 2020 is much higher (ranging from 44 to 53) than the number of facilities included in the Inventory for the 1990 to 2009 time period prior to the availability of GHGRP data (4 facilities). The difference is largely due to the fact the 1990 to 2009 data includes only CO_2 transferred to end-use applications from naturally occurring CO_2 reservoirs and excludes industrial sites.

1990 through 2009

For 1990 through 2009, data from EPA's GHGRP are not available. For this time period, CO_2 production data from four naturally-occurring CO_2 reservoirs were used to estimate annual CO_2 emissions. These facilities were Jackson Dome in Mississippi, Bravo and West Bravo Domes in New Mexico, and McCallum Dome in Colorado. The facilities in Mississippi and New Mexico produced CO_2 for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). The fourth facility in Colorado (McCallum Dome) produced CO_2 for commercial applications only (New Mexico Bureau of Geology and Mineral Resources 2006).

Carbon dioxide production data and the percentage of production that was used for non-EOR applications for the Jackson Dome, Mississippi facility were obtained from Advanced Resources International (ARI 2006, 2007) for 1990

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[53] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

to 2000, and from the Annual Reports of Denbury Resources (Denbury Resources 2002 through 2010) for 2001 to 2009 (see Table 4-54). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day for 2001 through 2009 and reported the percentage of the total average annual production that was used for EOR. Production from 1990 to 1999 was set equal to 2000 production, due to lack of publicly available production data for 1990 through 1999. Carbon dioxide production data for the Bravo Dome and West Bravo Dome were obtained from ARI for 1990 through 2009 (ARI 1990 to 2010). Data for the West Bravo Dome facility were only available for 2009. The percentage of total production that was used for non-EOR applications for the Bravo Dome and West Bravo Dome facilities for 1990 through 2009 were obtained from New Mexico Bureau of Geology and Mineral Resources (Broadhead 2003; New Mexico Bureau of Geology and Mineral Resources 2006). Production data for the McCallum Dome (Jackson County), Colorado facility were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) for 1999 through 2009 (COGCC 2014). Production data for 1990 to 1998 and percentage of production used for EOR were assumed to be the same as for 1999, due to lack of publicly available data.

Table 4-54: CO_2 Production (kt CO_2) and the Percent Used for Non-EOR Applications

Year	Jackson Dome, MS CO_2 Production (kt) (% Non-EOR)	Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	West Bravo Dome, NM CO_2 Production (kt) (% Non-EOR)	McCallum Dome, CO CO_2 Production (kt) (% Non-EOR)	Total CO_2 Production from Extraction and Capture Facilities (kt)	% Non-EOR[a]
1990	1,344 (100%)	63 (1%)	+	65 (100%)	NA	NA
2005	1,254 (27%)	58 (1%)	+	63 (100%)	NA	NA
2016	NA	NA	NA	NA	55,900[b]	8%
2017	NA	NA	NA	NA	59,900[b]	8%
2018	NA	NA	NA	NA	58,400[b]	7%
2019	NA	NA	NA	NA	61,300[b]	8%
2020	NA	NA	NA	NA	44,700[b]	11%

+ Does not exceed 0.5 percent.

NA (Not Available)

[a] Includes only food and beverage applications.

[b] For 2010 through 2020, the publicly available GHGRP data were aggregated at the national level based on GHGRP CBI criteria.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. The methodology for CO_2 consumption spliced activity data from two different sources: Industry data for 1990 through 2009 and GHGRP data starting in 2010. Consistent with the *2006 IPCC Guidelines*, the overlap technique was applied to compare the two data dets for years where there was overlap. The data sets were determined to be inconsistent; the GHGRP data includes CO_2 from industrial sources while the industry data does not. No adjustments were made to the activity data for 1990 through 2009 because the *2006 IPCC Guidelines* indicate that it is not good practice to use the overlap technique when the data sets are inconsistent.

Uncertainty

There is uncertainty associated with the data reported through EPA's GHGRP. Specifically, there is uncertainty associated with the amount of CO_2 consumed for food and beverage applications, given the GHGRP does have provisions that Subpart PP reporters are not required to report to the GHGRP if their emissions fall below certain thresholds, in addition to the exclusion of the amount of CO_2 transferred to all other end-use categories. This latter category might include CO_2 quantities that are being used for non-EOR industrial applications such as firefighting. Second, uncertainty is associated with the exclusion of imports/exports data for CO_2 suppliers. Currently these data are not publicly available through EPA's GHGRP and hence are excluded from this analysis. EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.

Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred.[54]

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-55. Carbon dioxide consumption CO_2 emissions for 2020 were estimated to be between 4.7 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 5.0 MMT CO_2 Eq.

Table 4-55: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from CO_2 Consumption (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO_2 Consumption	CO_2	5.0	4.7	5.2	-5%	+5%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). More details on the greenhouse gas calculation, monitoring and QA/QC methods applicable to CO_2 Consumption can be found under Subpart PP (Suppliers of Carbon Dioxide) of the regulation (40 CFR Part 98).[55] EPA verifies annual facility-level GHGRP reports through a multi-step process (e.g., combination of electronic checks and manual reviews) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[56] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

EPA will continue to evaluate the potential to include additional GHGRP data on other emissive end-uses to improve the accuracy and completeness of estimates for this source category. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[57]

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[54] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[55] See http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr98_main_02.tpl.

[56] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

[57] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

These improvements are still in process and will be incorporated into future Inventory reports. These are near-to medium-term improvements.

4.16 Phosphoric Acid Production (CRF Source Category 2B10)

Phosphoric acid (H_3PO_4) is a basic raw material used in the production of phosphate-based fertilizers. Phosphoric acid production from natural phosphate rock is a source of carbon dioxide (CO_2) emissions, due to the chemical reaction of the inorganic carbon (calcium carbonate) component of the phosphate rock.

Phosphate rock is mined in Florida and North Carolina, which account for more than 75 percent of total domestic output, and in Idaho and Utah (USGS 2021a). It is used primarily as a raw material for wet-process phosphoric acid production. The composition of natural phosphate rock varies, depending on the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic carbon in the form of calcium carbonate (limestone) and may also contain organic carbon.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). The generation of CO_2, however, is due to the associated limestone-sulfuric acid reaction, as shown below:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

Total U.S. phosphate rock production used in 2020 was an estimated 24.0 million metric tons (USGS 2021a). Total imports of phosphate rock to the United States in 2020 were 2.3 million metric tons (USGS 2021a). Between 2016 and 2019, most of the imported phosphate rock (85 percent) came from Peru, with 15 percent from Morocco (USGS 2021a). All phosphate rock mining companies in the United States are vertically integrated with fertilizer plants that produce phosphoric acid located near the mines. The phosphoric acid production facilities that use imported phosphate rock are located in Louisiana.

Over the 1990 to 2020 period, domestic phosphate rock production has decreased by nearly 52 percent. Total CO_2 emissions from phosphoric acid production were 0.9 MMT CO_2 Eq. (938 kt CO_2) in 2020 (see Table 4-56). Domestic consumption of phosphate rock in 2020 was estimated to have increased 3 percent relative to 2019 levels. The COVID-19 pandemic did not have a major effect on the domestic phosphate rock market as both the fertilizer industry and related agricultural businesses were considered essential industries (USGS 2021a).

Table 4-56: CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	1.5	1,529
2005	1.3	1,342
2016	1.0	998
2017	1.0	1,025
2018	0.9	937
2019	0.9	909
2020	0.9	938

Methodology and Time-Series Consistency

The United States uses a country-specific methodology consistent with an IPCC Tier 1 approach to calculate emissions from production of phosphoric acid from phosphate rock.[58] Carbon dioxide emissions from production of phosphoric acid from phosphate rock are estimated by multiplying the average amount of inorganic carbon (expressed as CO_2) contained in the natural phosphate rock as calcium carbonate by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption. The estimation methodology is as follows:

Equation 4-9: CO_2 Emissions from Phosphoric Acid Production

$$E_{pa} = C_{pr} \times Q_{pr}$$

where,

E_{pa} = CO_2 emissions from phosphoric acid production, metric tons
C_{pr} = Average amount of carbon (expressed as CO_2) in natural phosphate rock, metric ton CO_2/ metric ton phosphate rock
Q_{pr} = Quantity of phosphate rock used to produce phosphoric acid

The CO_2 emissions calculation methodology assumes that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to produce CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product.

From 1993 to 2004, the U.S. Geological Survey (USGS) *Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-57). For the years 1990 through 1992, and 2005 through 2019, only nationally aggregated mining data was reported by USGS. For the years 1990, 1991, and 1992, the breakdown of phosphate rock mined in Florida and North Carolina, and the amount mined in Idaho and Utah, are approximated using data reported by USGS for the average share of U.S. production in those states from 1993 to 2004. For the years 2005 through 2016 and years 2017 through 2020, the same approximation method is used, but the share of U.S. production based on production capacity in those states were obtained from the USGS commodity specialist for phosphate rock (USGS 2012; USGS 2021b). Data for domestic sales or consumption of phosphate rock, exports of phosphate rock (primarily from Florida and North Carolina), and imports of phosphate rock for consumption for 1990 through 2010 were obtained from USGS *Minerals Yearbook: Phosphate Rock* (USGS 1994 through 2015b), and from USGS *Minerals Commodity Summaries: Phosphate Rock* (USGS 2016 through 2021a). From 2004 through 2019, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2021a).

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research, now known as the Florida Industrial and Phosphate Research Institute (FIPR 2003a). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-58). Similar to the phosphate rock mined in Morocco, phosphate rock mined in Peru contains approximately 5 percent CO_2 (Golder Associates and M3 Engineering 2016).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (more than 75 percent of domestic production), and carbonate content data for phosphate rock mined in Morocco and Peru are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation assumes that all of the

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[58] The *2006 IPCC Guidelines* do not provide a method for estimating process emissions (CO_2) from Phosphoric Acid Production.

domestic production of phosphate rock is used in uncalcined form. As of 2006, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). The USGS confirmed that no significant quantity of domestic production of phosphate rock is in the calcined form (USGS 2012).

Table 4-57: Phosphate Rock Domestic Consumption, Exports, and Imports (kt)

Location/Year	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
U.S. Domestic Consumption	49,800	35,200	26,700	26,300	23,300	23,400	24,000
FL and NC	*42,494*	*28,160*	*21,360*	*20,510*	*18,170*	*18,250*	*18,720*
ID and UT	*7,306*	*7,040*	*5,340*	*5,790*	*5,130*	*5,150*	*5,280*
Exports—FL and NC	6,240	0	0	0	0	0	0
Imports	451	2,630	1,590	2,470	2,770	2,140	2,300
Total U.S. Consumption	**44,011**	**37,830**	**28,290**	**28,770**	**26,070**	**25,540**	**26,300**

Note: Totals may not sum due to independent rounding.

Table 4-58: Chemical Composition of Phosphate Rock (Percent by Weight)

Composition	**Central Florida**	**North Florida**	**North Carolina (calcined)**	**Idaho (calcined)**	**Morocco**	**Peru**
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56	NA
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46	NA
Organic Carbon (as C)	0.60	0.83	0.35	0.00	0.10	NA
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00	5.00

NA (Not Available)

Sources: FIPR (2003a), Golder Associates and M3 Engineering (2016)

Methodological approaches were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2020.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2019. Prior to 2006, USGS provided the data disaggregated regionally; however, beginning in 2006, only total U.S. phosphate rock production was reported. Regional production for 2020 was estimated based on regional production data from 2017 to 2020 and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2019 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for exports of phosphate rock used in the emission calculations are reported to the USGS by phosphate rock producers and are not considered to be a significant source of uncertainty. Data for imports for consumption are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock, as the composition of phosphate rock varies depending upon where the material is mined and may also vary over time. The Inventory relies on one study (FIPR 2003a) of chemical composition of the phosphate rock; limited data are available beyond this study. Another source of uncertainty is the disposition of the organic carbon content of the phosphate rock. A representative of FIPR indicated that in the phosphoric acid production process the organic C content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003b). Organic carbon is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic C in the phosphate rock into CO_2. However, according to air permit information available to the public, at least one facility has calcining units permitted for operation (NCDENR 2013).

Finally, USGS indicated that in 2020 less than 5 percent of domestically-produced phosphate rock was used to manufacture elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2021a). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions assumes that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic carbon content in phosphate rock, but none from the organic carbon content.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-59. 2020 phosphoric acid production CO_2 emissions were estimated to be between 0.8 and 1.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 20 percent above the emission estimate of 0.9 MMT CO_2 Eq.

Table 4-59: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	0.9	0.8	1.2	-18%	+20%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details).

Recalculations Discussion

Recalculations were performed for the 2017 through 2019 portion of the time series to reflect an updated breakdown of phosphate rock mined in Florida and North Carolina and the amount mined in Idaho and Utah as provided by the USGS commodity specialist. Additionally, the 2019 value for the total U.S. production of phosphate rock was updated based on updated USGS data. These updates resulted in minor decreases of 3 kt CO_2 in both 2017 and 2018 and an increase of 18 kt CO_2 in 2019.

Planned Improvements

EPA continues to evaluate potential improvements to the Inventory estimates for this source category, which include direct integration of EPA's GHGRP data for 2010 through 2020 along with assessing applicability of reported GHGRP data to update the inorganic C content of phosphate rock for prior years to ensure time-series consistency. Specifically, EPA would need to assess that averaged inorganic C content data (by region or other approaches) meets GHGRP confidential business information (CBI) screening criteria. EPA would then need to assess the applicability of GHGRP data for the averaged inorganic C content (by region or other approaches) from 2010 through 2020, along with other information to inform estimates in prior years in the required time series

(1990 through 2009) based on the sources of phosphate rock used in production of phosphoric acid over time. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[59] These long-term planned improvements are still in development by EPA and have not been implemented into the current Inventory report.

4.17 Iron and Steel Production (CRF Source Category 2C1) and Metallurgical Coke Production

Iron and steel production is a multi-step process that generates process-related emissions of carbon dioxide (CO_2) and methane (CH_4) as raw materials are refined into iron and then transformed into crude steel. Emissions from conventional fuels (e.g., natural gas, fuel oil) consumed for energy purposes during the production of iron and steel are accounted for in the Energy chapter.

Iron and steel production includes seven distinct production processes: metallurgical coke production, sinter production, direct reduced iron (DRI) production, pellet production, pig iron[60] production, electric arc furnace (EAF) steel production, and basic oxygen furnace (BOF) steel production. The number of production processes at a particular plant is dependent upon the specific plant configuration. Most process CO_2 generated from the iron and steel industry is a result of the production of crude iron.

In addition to the production processes mentioned above, CO_2 is also generated at iron and steel mills through the consumption of process byproducts (e.g., blast furnace gas, coke oven gas) used for various purposes including heating, annealing, and electricity generation. Process byproducts sold off-site for use as synthetic natural gas are also accounted for in these calculations. In general, CO_2 emissions are generated in these production processes through the reduction and consumption of various carbon-containing inputs (e.g., ore, scrap, flux, coke byproducts). Fugitive CH_4 emissions can also be generated from these processes, as well as from sinter, direct iron, and pellet production.

In 2020, approximately eleven integrated iron and steel steelmaking facilities utilized BOFs to refine and produce steel from iron, and raw steel was produced at 98 facilities across the United States. Approximately 30 percent of steel production was attributed to BOFs and 70 percent to EAFs (USGS 2021). The trend in the United States for integrated facilities has been a shift towards fewer BOFs and more EAFs. EAFs use scrap steel as their main input and use significantly less energy than BOFs. There are also 14 cokemaking facilities, of which 3 facilities are co-located with integrated iron and steel facilities (ACCCI 2021). In the United States, 6 states account for roughly 51 percent of total raw steel production: Indiana, Alabama, Tennessee, Kentucky, Mississippi, and Arkansas (AISI 2021).

Total annual production of crude steel in the United States was fairly constant between 2000 and 2008 and ranged from a low of 99,320,000 tons to a high of 109,880,000 tons (2001 and 2004, respectively). Due to the decrease in demand caused by the global economic downturn (particularly from the automotive industry), crude steel production in the United States sharply decreased to 65,459,000 tons in 2009. Crude steel production was fairly constant from 2011 through 2014, and after a dip in production from 2014 to 2015, crude steel production has slowly and steadily increased for the past few years. The United States was the fourth largest producer of raw steel

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[59] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[60] Pig iron is the common industry term to describe what should technically be called crude iron. Pig iron is a subset of crude iron that has lost popularity over time as industry trends have shifted. Throughout this report, pig iron will be used interchangeably with crude iron, but it should be noted that in other data sets or reports pig iron and crude iron may not be used interchangeably and may provide different values.

in the world, behind China, India and Japan, accounting for approximately 3.9 percent of world production in 2020 (AISI 2004 through 2021).

The majority of CO_2 emissions from the iron and steel production process come from the use of metallurgical coke in the production of pig iron and from the consumption of other process byproducts, with lesser amounts emitted from the use of carbon-containing flux and from the removal of carbon from pig iron used to produce steel.

According to the *2006 IPCC Guidelines*, the production of metallurgical coke from coking coal is considered to be an energy use of fossil fuel, and the use of coke in iron and steel production is considered to be an industrial process source. The *2006 IPCC Guidelines* suggest that emissions from the production of metallurgical coke should be reported separately in the Energy sector, while emissions from coke consumption in iron and steel production should be reported in the Industrial Processes and Product Use sector. The approaches and emission estimates for both metallurgical coke production and iron and steel production, however, are presented here because much of the relevant activity data is used to estimate emissions from both metallurgical coke production and iron and steel production. For example, some byproducts (e.g., coke oven gas) of the metallurgical coke production process are consumed during iron and steel production, and some byproducts of the iron and steel production process (e.g., blast furnace gas) are consumed during metallurgical coke production. Emissions associated with the consumption of these byproducts are attributed at the point of consumption. Emissions associated with the use of conventional fuels (e.g., natural gas, fuel oil) for electricity generation, heating and annealing, or other miscellaneous purposes downstream of the iron and steelmaking furnaces are reported in the Energy chapter.

Metallurgical Coke Production

Emissions of CO_2 from metallurgical coke production in 2020 were 2.3 MMT CO_2 Eq. (2,324 kt CO_2) (see Table 4-60 and Table 4-61). Emissions decreased by 23 percent from 2019 to 2020 and have decreased by 59 percent since 1990. Coke production in 2020 was about 20 percent lower than in 2019 and 63 percent below 1990 (EIA 2021, AISI 2021).

Significant activity data for 2020 were not available in time for publication of this report and were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

Table 4-60: CO_2 Emissions from Metallurgical Coke Production (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	5.6	3.9	2.6	2.0	1.3	3.0	2.3

Table 4-61: CO_2 Emissions from Metallurgical Coke Production (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	5,608	3,921	2,643	1,978	1,282	3,006	2,324

Iron and Steel Production

Emissions of CO_2 and CH_4 from iron and steel production in 2020 were 35.4 MMT CO_2 Eq. (35,386 kt) and 0.0066 MMT CO_2 Eq. (0.3 kt CH_4), respectively (see Table 4-62 through Table 4-65), totaling 35.4 MMT CO_2 Eq. Emissions from iron and steel production decreased by 12 percent from 2019 to 2020 and have decreased by 64 percent since 1990, due to restructuring of the industry, technological improvements, and increased scrap steel utilization. Carbon dioxide emission estimates include emissions from the consumption of carbonaceous materials in the blast furnace, EAF, and BOF, as well as blast furnace gas and coke oven gas consumption for other activities at the steel mill.

Significant activity data for 2020 were not available in time for publication of this report and were estimated using 2019 values adjusted based on GHGRP emissions data, as described in the Methodology and Time-Series Consistency section below.

In 2020, domestic production of pig iron decreased by 18 percent from 2019 levels. Overall, domestic pig iron production has declined since the 1990s. Pig iron production in 2020 was 62 percent lower than in 2000 and 63 percent below 1990. Carbon dioxide emissions from iron production have decreased by 82 percent (37.3 MMT CO_2 Eq.) since 1990. Carbon dioxide emissions from steel production have decreased by 29 percent (2.3 MMT CO_2 Eq.) since 1990, while overall CO_2 emissions from iron and steel production have declined by 64 percent (63.7 MMT CO_2 Eq.) from 1990 to 2020.

Table 4-62: CO_2 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Sinter Production	2.4	1.7	0.9	0.9	0.9	0.9	0.8
Iron Production	45.7	17.7	9.9	8.2	9.6	9.4	8.4
Pellet Production	1.8	1.5	0.9	0.9	0.9	0.9	0.8
Steel Production	8.0	9.4	6.9	6.2	5.8	5.8	5.6
Other Activities[a]	41.2	35.9	22.5	22.4	24.1	23.2	19.8
Total	**99.1**	**66.2**	**41.0**	**38.6**	**41.3**	**40.1**	**35.4**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-63: CO_2 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Sinter Production	2,448	1,663	877	869	937	876	750
Iron Production	45,706	17,661	9,928	8,237	9,581	9,360	8,416
Pellet Production	1,817	1,503	869	867	924	878	752
Steel Production	7,964	9,395	6,854	6,218	5,754	5,812	5,650
Other Activities[a]	41,194	35,934	22,451	22,396	24,149	23,158	19,838
Total	**99,129**	**66,156**	**40,979**	**38,587**	**41,345**	**40,084**	**35,407**

[a] Includes emissions from blast furnace gas and coke oven gas combustion for activities at the steel mill other than consumption in blast furnace, EAFs, or BOFs.

Note: Totals may not sum due to independent rounding.

Table 4-64: CH_4 Emissions from Iron and Steel Production (MMT CO_2 Eq.)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Sinter Production	+	+	+	+	+	+	+

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-65: CH_4 Emissions from Iron and Steel Production (kt)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Sinter Production	0.9	0.6	0.3	0.3	0.3	0.3	0.3

Methodology and Time-Series Consistency

Emission estimates presented in this chapter utilize a country-specific approach based on Tier 2 methodologies provided by the *2006 IPCC Guidelines*. These Tier 2 methodologies call for a mass balance accounting of the carbonaceous inputs and outputs during the iron and steel production process and the metallurgical coke production process. Tier 1 methods are used for certain iron and steel production processes (i.e., sinter production, pellet production and DRI production) for which available data are insufficient to apply a Tier 2 method (e.g., country-specific carbon contents of inputs and outputs are not known). The majority of emissions are captured with higher tier methods, as sinter production, pellet production, and DRI production only account for roughly 8 percent of total iron and steel production emissions.

The Tier 2 methodology equation is as follows:

Equation 4-10: CO_2 Emissions from Coke, Pig Iron, EAF Steel, and BOF Steel Production, based on *2006 IPCC Guidelines* Tier 2 Methodologies

$$E_{CO_2} = \left[\sum_a (Q_a \times C_a) - \sum_b (Q_b \times C_b)\right] \times \frac{44}{12}$$

where,

E_{CO2} = Emissions from coke, pig iron, EAF steel, or BOF steel production, metric tons
a = Input material *a*
b = Output material *b*
Q_a = Quantity of input material *a*, metric tons
C_a = Carbon content of input material *a*, metric tons C/metric ton material
Q_b = Quantity of output material *b*, metric tons
C_b = Carbon content of output material *b*, metric tons C/metric ton material
44/12 = Stoichiometric ratio of CO_2 to C

The Tier 1 methodology equations are as follows:

Equation 4-11: *2006 IPCC Guidelines* Tier 1: Emissions from Sinter, Direct Reduced Iron, and Pellet Production (Equations 4.6, 4.7, and 4.8)

$$E_{s,p} = Q_s \times EF_{s,p}$$

$$E_{d,CO2} = Q_d \times EF_{d,CO2}$$

$$E_{p,CO2} = Q_p \times EF_{p,CO2}$$

where,

$E_{s,p}$ = Emissions from sinter production process for pollutant *p* (CO_2 or CH_4), metric ton
Q_s = Quantity of sinter produced, metric tons
$EF_{s,p}$ = Emission factor for pollutant *p* (CO_2 or CH_4), metric ton *p*/metric ton sinter
$E_{d,CO2}$ = Emissions from DRI production process for CO_2, metric ton
Q_d = Quantity of DRI produced, metric tons
$EF_{d,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton DRI
$E_{p,CO2}$ = Emissions from pellet production process for CO_2, metric ton
Q_p = Quantity of pellets produced, metric tons
$EF_{p,CO2}$ = Emission factor for CO_2, metric ton CO_2/metric ton pellets produced

A significant number of activity data that serve as inputs to emissions calculations were unavailable for 2020 at the time of publication and were estimated using 2019 values. In addition, to account for the impacts of the COVID-19 pandemic in 2020, the EPA used process emissions data from the EPA's Greenhouse Gas Reporting Program (GHGRP) subpart Q for the iron and steel sector to adjust the estimated values. GHGRP process emissions data decreased by approximately 14 percent from 2019 to 2020 (EPA 2021), and this percentage decrease was applied to all 2020 activity data estimated with 2019 values.

Metallurgical Coke Production

Coking coal is used to manufacture metallurgical coke which is used primarily as a reducing agent in the production of iron and steel but is also used in the production of other metals including zinc and lead (see Zinc Production and Lead Production sections of this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated and reported separately from emissions that result from the iron and steel production process. To estimate emissions from metallurgical coke production, a Tier 2 method provided by the *2006 IPCC Guidelines* was utilized. The amount of carbon contained in materials produced during the metallurgical coke production process (i.e., coke, coke breeze and coke oven gas) is deducted from the amount of carbon contained in materials consumed during the metallurgical coke production process (i.e., natural gas, blast furnace gas, and coking coal). For calculations, activity data for these inputs, including natural gas, blast furnace gas, and coking coke consumed for metallurgical coke production, are in units consistent with the carbon content values. Light oil, which is produced during the metallurgical coke production process, is excluded from the deductions due to data limitations. The amount of carbon contained in these materials is calculated by multiplying the material-specific carbon content by the amount of material consumed or produced (see Table 4-66). The amount of coal tar produced was approximated using a production factor of 0.03 tons of coal tar per ton of coking coal consumed. The amount of coke breeze produced was approximated using a production factor of 0.075 tons of coke breeze per ton of coking coal consumed (Steiner 2008; DOE 2000). Data on the consumption of carbonaceous materials (other than coking coal) as well as coke oven gas production were available for integrated steel mills only (i.e., steel mills with co-located coke plants); therefore, carbonaceous material (other than coking coal) consumption and coke oven gas production were excluded from emission estimates for merchant coke plants. Carbon contained in coke oven gas used for coke-oven underfiring was not included in the deductions to avoid double-counting.

Table 4-66: Material Carbon Contents for Metallurgical Coke Production

Material	**kg C/kg**
Coal Tar[a]	0.62
Coke[a]	0.83
Coke Breeze[a]	0.83
Coking Coal[b]	0.75
Material	**kg C/GJ**
Coke Oven Gas[c]	12.1
Blast Furnace Gas[c]	70.8

[a] Source: IPCC (2006), Vol. 3 Chapter 4, Table 4.3

[b] Source: EIA (2017b)

[c] Source: IPCC (2006), Vol. 2 Chapter 1, Table 1.3

Although the *2006 IPCC Guidelines* provide a Tier 1 CH_4 emission factor for metallurgical coke production (i.e., 0.1 g CH_4 per metric ton of coke production), it is not appropriate to use because CO_2 emissions were estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the metallurgical coke production process either exits the process as part of a carbon-containing output or as CO_2 emissions. This is consistent with a preliminary assessment of aggregated facility-level greenhouse gas CH_4 emissions reported by coke production facilities under EPA's GHGRP. The assessment indicates that CH_4 emissions from coke production are insignificant and below 500 kt or 0.05 percent of total national emissions. Pending resources and significance, EPA continues to assess the possibility of including these emissions in future Inventories to enhance completeness but has not incorporated these emissions into this report.

Data relating to the mass of coking coal consumed at metallurgical coke plants and the mass of metallurgical coke produced at coke plants were taken from the Energy Information Administration (EIA) *Quarterly Coal Report: October through December* (EIA 1998 through 2019) and EIA *Quarterly Coal Report: January through March* (EIA 2021) (see Table 4-67). Data on the volume of natural gas consumption, blast furnace gas consumption, and coke oven gas production for metallurgical coke production at integrated steel mills were obtained from the American Iron and Steel Institute (AISI) *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-68). Coke plant consumption and production data from the AISI Annual Statistical Report were withheld for 2020, so the 2019 values were used as estimated data for the missing 2020 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

The factor for the quantity of coal tar produced per ton of coking coal consumed was provided by AISI (Steiner 2008). The factor for the quantity of coke breeze produced per ton of coking coal consumed was obtained through Table 2-1 of the report *Energy and Environmental Profile of the U.S. Iron and Steel Industry* (DOE 2000). Currently, data on natural gas consumption and coke oven gas production at merchant coke plants were not available and were excluded from the emission estimate. Carbon contents for metallurgical coke, coal tar, coke oven gas, and blast furnace gas were provided by the *2006 IPCC Guidelines*. The carbon content for coke breeze was assumed to equal the carbon content of coke. Carbon contents for coking coal was from EIA.

Table 4-67: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Metallurgical Coke Production							
Coking Coal Consumption at Coke Plants	35,269	21,259	14,955	15,910	16,635	16,261	13,076
Coke Production at Coke Plants	25,054	15,167	10,755	11,746	12,525	11,676	9,392
Coke Breeze Production	2,645	1,594	1,122	1,193	1,248	1,220	981
Coal Tar Production	1,058	638	449	477	499	488	392

Table 4-68: Production and Consumption Data for the Calculation of CO_2 Emissions from Metallurgical Coke Production (Million ft^3)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Metallurgical Coke Production							
Coke Oven Gas Production	250,767	114,213	74,807	74,997	80,750	77,692	66,554
Natural Gas Consumption	599	2,996	2,077	2,103	2,275	2,189	1,875
Blast Furnace Gas Consumption	24,602	4,460	3,741	3,683	4,022	3,914	3,353

Iron and Steel Production

To estimate emissions from pig iron production in the blast furnace, the amount of carbon contained in the produced pig iron and blast furnace gas were deducted from the amount of carbon contained in inputs (i.e., metallurgical coke, sinter, natural ore, pellets, natural gas, fuel oil, coke oven gas, carbonate fluxes or slagging materials, and direct coal injection). For calculations, activity data for these inputs, including coke consumed for pig iron production, are in units consistent with the carbon content values. The carbon contained in the pig iron, blast furnace gas, and blast furnace inputs was estimated by multiplying the material-specific carbon content by each material type (see Table 4-69). In the absence of a default carbon content value from the *2006 IPCC Guidelines* for pellet, sinter, or natural ore consumed for pig iron production, a country-specific approach based on Tier 2 methodology is used. Pellet, sinter, and natural ore used as an input for pig iron production is assumed to have the same carbon content as direct reduced iron (2 percent). Carbon in blast furnace gas used to pre-heat the blast furnace air is combusted to form CO_2 during this process. Carbon contained in blast furnace gas used as a blast furnace input was not included in the deductions to avoid double-counting.

Emissions from steel production in EAFs were estimated by deducting the carbon contained in the steel produced from the carbon contained in the EAF anode, charge carbon, and scrap steel added to the EAF. Small amounts of carbon from DRI and pig iron to the EAFs were also included in the EAF calculation. For BOFs, estimates of carbon contained in BOF steel were deducted from carbon contained in inputs such as natural gas, coke oven gas, fluxes (i.e., limestone and dolomite), and pig iron. In each case, the carbon was calculated by multiplying material-specific carbon contents by each material type (see Table 4-69). For EAFs, the amount of EAF anode consumed was approximated by multiplying total EAF steel production by the amount of EAF anode consumed per metric ton of steel produced (0.002 metric tons EAF anode per metric ton steel produced [Steiner 2008]). The amount of carbon-containing flux (i.e., limestone and dolomite) used in pig iron production was deducted from the "Other Process Uses of Carbonates" source category (CRF Source Category 2A4) to avoid double-counting.

Carbon dioxide emissions from the consumption of blast furnace gas and coke oven gas for other activities occurring at the steel mill were estimated by multiplying the amount of these materials consumed for these purposes by the material-specific carbon content (see Table 4-69).

Table 4-69: Material Carbon Contents for Iron and Steel Production

Material	kg C/kg
Coke	0.83
Direct Reduced Iron	0.02
Dolomite	0.13
EAF Carbon Electrodes	0.82
EAF Charge Carbon	0.83
Limestone	0.12
Pig Iron	0.04
Steel	0.01
Material	**kg C/GJ**
Coke Oven Gas	12.1
Blast Furnace Gas	70.8

Source: IPCC (2006), Table 4.3. Coke Oven Gas and Blast Furnace Gas, Table 1.3.

Carbon dioxide emissions associated with sinter production, direct reduced iron production, pellet production, pig iron production, steel production, and other steel mill activities were summed to calculate the total CO_2 emissions from iron and steel production (see Table 4-62 and Table 4-63).

The sinter production process results in fugitive emissions of CH_4, which are emitted via leaks in the production equipment, rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying Tier 1 emission factors taken from the *2006 IPCC Guidelines* for sinter production (see Table 4-70). Although the *2006 IPCC Guidelines* also provide a Tier 1 methodology for CH_4 emissions from pig iron production, it is not appropriate to use because CO_2 emissions for pig iron production are estimated using the Tier 2 mass balance methodology. The mass balance methodology makes a basic assumption that all carbon that enters the pig iron production process either exits the process as part of a carbon-containing output or as CO_2 emissions; the estimation of CH_4 emissions is precluded. Annual analysis of facility-level emissions reported during iron production further supports this assumption and indicates that CH_4 emissions are below 500 kt CO_2 Eq. and well below 0.05 percent of total national emissions. The production of direct reduced iron could also result in emissions of CH_4 through the consumption of fossil fuels (e.g., natural gas, etc.); however, these emission estimates are excluded due to data limitations. Pending further analysis and resources, EPA may include these emissions in future reports to enhance completeness. EPA is still assessing the possibility of including these emissions in future reports and have not included this data in the current report.

Table 4-70: CH_4 Emission Factors for Sinter and Pig Iron Production

Material Produced	Factor	Unit
Sinter	0.07	kg CH_4/metric ton

Source: IPCC (2006), Table 4.2.

Emissions of CO_2 from sinter production, direct reduced iron production, and pellet production were estimated by multiplying total national sinter production, total national direct reduced iron production, and total national pellet production by Tier 1 CO_2 emission factors (see Table 4-71). Because estimates of sinter production, direct reduced iron production, and pellet production were not available, production was assumed to equal consumption.

Table 4-71: CO_2 Emission Factors for Sinter Production, Direct Reduced Iron Production, and Pellet Production

Material Produced	Metric Ton CO_2/Metric Ton
Sinter	0.2
Direct Reduced Iron	0.7
Pellet Production	0.03

Source: IPCC (2006), Table 4.1.

The consumption of coking coal, natural gas, distillate fuel, and coal used in iron and steel production are adjusted for within the Energy chapter to avoid double-counting of emissions reported within the IPPU chapter as these fuels were consumed during non-energy related activities. More information on this methodology and examples of adjustments made between the IPPU and Energy chapters are described in Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Sinter consumption and pellet consumption data for 1990 through 2020 were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-72). Data from the AISI Annual Statistical Report were withheld for 2020, so the 2019 values were used as estimated data for the missing 2020 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

In general, direct reduced iron (DRI) consumption data were obtained from the U.S. Geological Survey (USGS) *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2020) and personal communication with the USGS Iron and Steel Commodity Specialist (Tuck 2020); however, data for DRI consumed in EAFs were not available for the years 1990 and 1991. EAF DRI consumption in 1990 and 1991 was calculated by multiplying the total DRI consumption for all furnaces by the EAF share of total DRI consumption in 1992. Also, data for DRI consumed in BOFs were not available for the years 1990 through 1993. BOF DRI consumption in 1990 through 1993 was calculated by multiplying the total DRI consumption for all furnaces (excluding EAFs and cupola) by the BOF share of total DRI consumption (excluding EAFs and cupola) in 1994.

The Tier 1 CO_2 emission factors for sinter production, direct reduced iron production and pellet production were obtained through the *2006 IPCC Guidelines* (IPCC 2006). Time-series data for pig iron production, coke, natural gas, fuel oil, sinter, and pellets consumed in the blast furnace; pig iron production; and blast furnace gas produced at the iron and steel mill and used in the metallurgical coke ovens and other steel mill activities were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008) (see Table 4-72 and Table 4-73). Some data from the AISI Annual Statistical Report were withheld for 2020, so the 2019 values were used as estimated data for the missing 2020 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data for EAF steel production, carbon-containing flux, EAF charge carbon, and natural gas consumption were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (AISI 2006 through 2016, Steiner 2008). The factor for the quantity of EAF anode consumed per ton of EAF steel produced was provided by AISI (Steiner 2008). Data for BOF steel production, carbon-containing flux, natural gas, natural ore, pellet, sinter consumption as well as BOF steel production were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). Data for EAF and BOF scrap steel, pig iron, and DRI consumption were obtained from the USGS *Minerals Yearbook – Iron and Steel Scrap* (USGS 1991 through 2020). Data on coke oven gas and blast furnace gas consumed at the iron and steel mill (other than in the EAF, BOF, or blast furnace) were obtained from AISI's *Annual Statistical Report* (AISI 2004 through 2021) and through personal communications with AISI (Steiner 2008). Some data from the AISI Annual Statistical Report on natural gas consumption were withheld for 2020, so the 2019 values were used as estimated data for the missing 2020 values and adjusted using GHGRP emissions data, as described earlier in this Methodology and Time-Series Consistency section.

Data on blast furnace gas and coke oven gas sold for use as synthetic natural gas were obtained from EIA's *Natural Gas Annual* (EIA 2020). Carbon contents for direct reduced iron, EAF carbon electrodes, EAF charge carbon, limestone, dolomite, pig iron, and steel were provided by the *2006 IPCC Guidelines*. The carbon contents for natural gas, fuel oil, and direct injection coal were obtained from EIA (EIA 2017b) and EPA (EPA 2010). Heat contents for fuel oil and direct injection coal were obtained from EIA (EIA 1992, 2011); natural gas heat content was obtained from Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021). Heat contents for coke oven gas and blast furnace gas were provided in Table 37 of AISI's *Annual Statistical Report* (AISI 2004 through 2021) and confirmed by AISI staff (Carroll 2016).

Table 4-72: Production and Consumption Data for the Calculation of CO_2 and CH_4 Emissions from Iron and Steel Production (Thousand Metric Tons)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Sinter Production	12,239	8,315	4,385	4,347	4,687	4,378	3,751
Direct Reduced Iron Production	517	1,303	C	C	C	C	C
Pellet Production	60,563	50,096	28,967	28,916	30,793	29,262	25,067
Pig Iron Production							
Coke Consumption	24,946	13,832	7,124	7,101	7,618	7,291	6,246
Pig Iron Production	49,669	37,222	22,293	22,395	24,058	22,302	18,320
Direct Injection Coal Consumption	1,485	2,573	1,935	2,125	2,569	2,465	2,112
EAF Steel Production							
EAF Anode and Charge Carbon Consumption	67	1,127	1,120	1,127	1,133	1,137	1,118
Scrap Steel Consumption	42,691	46,600	C	C	C	C	C
Flux Consumption	319	695	998	998	998	998	998
EAF Steel Production	33,511	52,194	52,589	55,825	58,904	61,172	51,349
BOF Steel Production							
Pig Iron Consumption	47,307	34,400	C	C	C	C	C
Scrap Steel Consumption	14,713	11,400	C	C	C	C	C
Flux Consumption	576	582	408	408	408	363	311
BOF Steel Production	43,973	42,705	25,888	25,788	27,704	26,591	21,383

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Table 4-73: Production and Consumption Data for the Calculation of CO_2 Emissions from Iron and Steel Production (Million ft^3 unless otherwise specified)

Source/Activity Data	1990	2005	2016	2017	2018	2019	2020
Pig Iron Production							
Natural Gas Consumption	56,273	59,844	38,396	38,142	40,204	37,934	32,496
Fuel Oil Consumption (thousand gallons)	163,397	16,170	6,124	4,352	3,365	2,321	1,988
Coke Oven Gas Consumption	22,033	16,557	12,404	12,459	13,337	12,926	11,073
Blast Furnace Gas Production	1,439,380	1,299,980	811,005	808,499	871,860	836,033	716,182
EAF Steel Production							
Natural Gas Consumption	15,905	19,985	3,915	8,105	8,556	9,115	7,808
BOF Steel Production							
Coke Oven Gas Consumption	3,851	524	367	374	405	389	333
Other Activities							

Coke Oven Gas Consumption	224,883	97,132	62,036	62,164	67,008	64,377	55,148
Blast Furnace Gas Consumption	1,414,778	1,295,520	807,264	804,816	867,838	832,119	712,829

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

The estimates of CO_2 emissions from metallurgical coke production are based on assessing uncertainties in material production and consumption data and average carbon contents. Uncertainty is associated with the total U.S. coking coal consumption, total U.S. coke production, and materials consumed during this process. Data for coking coal consumption and metallurgical coke production are from different data sources (EIA) than data for other carbonaceous materials consumed at coke plants (AISI), which does not include data for merchant coke plants. There is uncertainty associated with the fact that coal tar and coke breeze production were estimated based on coke production because coal tar and coke breeze production data were not available. Since merchant coke plant data is not included in the estimate of other carbonaceous materials consumed at coke plants, the mass balance equation for CO_2 from metallurgical coke production cannot be reasonably completed; therefore, for the purpose of this analysis, uncertainty parameters are applied to primary data inputs to the calculation (i.e., coking coal consumption and metallurgical coke production) only.

The estimates of CO_2 emissions from iron and steel production are based on material production and consumption data and average carbon contents. There is uncertainty associated with the assumption that pellet production, direct reduced iron and sinter consumption are equal to production. There is uncertainty with the representativeness of the associated IPCC default emission factors. There is uncertainty associated with the assumption that all coal used for purposes other than coking coal is for direct injection coal. There is also uncertainty associated with the carbon contents for pellets, sinter, and natural ore, which are assumed to equal the carbon contents of direct reduced iron, when consumed in the blast furnace. There is uncertainty associated with the consumption of natural ore under current industry practices. For EAF steel production, there is uncertainty associated with the amount of EAF anode and charge carbon consumed due to inconsistent data throughout the time series. Also for EAF steel production, there is uncertainty associated with the assumption that 100 percent of the natural gas attributed to “steelmaking furnaces” by AISI is process-related and nothing is combusted for energy purposes. Uncertainty is also associated with the use of process gases such as blast furnace gas and coke oven gas. Data are not available to differentiate between the use of these gases for processes at the steel mill versus for energy generation (i.e., electricity and steam generation); therefore, all consumption is attributed to iron and steel production. These data and carbon contents produce a relatively accurate estimate of CO_2 emissions; however, there are uncertainties associated with each.

For calculating the emissions estimates from iron and steel and metallurgical coke production, EPA utilizes a number of data points taken from the AISI *Annual Statistical Report* (ASR). This report serves as a benchmark for information on steel companies in United States, regardless if they are a member of AISI, which represents integrated producers (i.e., blast furnace and EAF). During the compilation of the 1990 through 2016 Inventory report EPA initiated conversation with AISI to better understand and update the qualitative and quantitative uncertainty metrics associated with AISI data elements. AISI estimates their data collection response rate to range from 75 to 90 percent, with certain sectors of the iron and steel industry not being covered by the ASR; therefore, there is some inherent uncertainty in the values provided in the AISI ASR, including material production and consumption data. There is also some uncertainty to which materials produced are exported to Canada. As indicated in the introduction to this section, the trend for integrated facilities has moved to more use of EAFs and fewer BOFs. This trend may not be completely captured in the current data which also increases uncertainty. EPA currently uses an uncertainty range of ±10 percent for the primary data inputs (e.g., consumption and production values for each production process, heat and carbon content values) to calculate overall uncertainty from iron and steel production, consistent with the ranges in Table 4.4 of the *2006 IPCC Guidelines*. During EPA’s discussion with

AISI, AISI noted that an uncertainty range of ±5 percent would be a more appropriate approximation to reflect their coverage of integrated steel producers in the United States. EPA will continue to assess the best range of uncertainty for these values. Consistent with the ranges in Table 4.4 of the *2006 IPCC Guidelines*, EPA assigned an uncertainty range of ±25 percent for the Tier 1 CO_2 emission factors for the sinter, direct reduced iron, and pellet production processes.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-74 for metallurgical coke production and iron and steel production. Total CO_2 emissions from metallurgical coke production and iron and steel production for 2020 were estimated to be between 31.4 and 44.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below and 17 percent above the emission estimate of 35.4 MMT CO_2 Eq. Total CH_4 emissions from metallurgical coke production and iron and steel production for 2020 were estimated to be between 0.005 and 0.008 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 23 percent above the emission estimate of 0.007 MMT CO_2 Eq.

Table 4-74: Approach 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production and Metallurgical Coke Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Metallurgical Coke & Iron and Steel Production	CO_2	35.4	31.4	44.2	-17%	+17%
Metallurgical Coke & Iron and Steel Production	CH_4	+	+	+	-21%	+23%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

Recalculations were performed for the year 2019 with updated values for coke production at coke plants, scrap steel consumption for EAF steel production, scrap steel consumption for BOF steel production, and pellet consumption in blast furnaces from EIA, USGS, and AISI. These updates resulted in emissions increases of 114 percent from metallurgical coke production (1.6 MMT CO_2), less than 1 percent from iron production (87 kt CO_2), 1.2 percent from pellet production (11 kt CO_2), and less than 1 percent from steel production (42 kt CO_2).

Planned Improvements

Significant activity data for 2020 were not available for this report and were estimated using 2019 values and adjusted using GHGRP emissions data. EPA will continue to explore sources of 2020 data and other estimation approaches if 2020 data is not available for the next Inventory report. EPA will update the calculations for the 2023 Inventory submission if new data becomes available.

Future improvements involve improving activity data and emission factor sources for CO_2 and CH_4 emissions estimations from pellet production. EPA will also evaluate and analyze data reported under EPA's GHGRP to improve the emission estimates for this and other Iron and Steel Production process categories. Particular attention will be made to ensure time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's

GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[61] This remains a medium-term improvement, and per preliminary work, EPA estimates that the earliest this improvement could be incorporated is the 2024 Inventory submission.

Additional improvements include accounting for emission estimates for the production of metallurgical coke in the Energy chapter as well as identifying the amount of carbonaceous materials, other than coking coal, consumed at merchant coke plants. Other potential improvements include identifying the amount of coal used for direct injection and the amount of coke breeze, coal tar, and light oil produced during coke production. Efforts will also be made to identify information to better characterize emissions from the use of process gases and fuels within the Energy and IPPU chapters. Additional efforts will be made to improve the reporting between the IPPU and Energy chapters, particularly the inclusion of a quantitative summary of the carbon balance in the United States. This planned improvement is a long-term improvement and is still in development. It is not included in this current Inventory report and is not expected until a future (i.e., 2024) Inventory submission.

EPA also received comments during the Expert Review cycle of a previous (i.e., 1990 through 2016) Inventory on recommendations to improve the description of the iron and steel industry and emissive processes. EPA began incorporating some of these recommendations into a previous Inventory (i.e., 1990 through 2016) and will require some additional time to implement other substantive changes.

4.18 Ferroalloy Production (CRF Source Category 2C2)

Carbon dioxide (CO_2) and methane (CH_4) are emitted from the production of several ferroalloys. Ferroalloys are composites of iron (Fe) and other elements such as silicon (Si), manganese (Mn), and chromium (Cr). Emissions from fuels consumed for energy purposes during the production of ferroalloys are accounted for in the Energy chapter. Emissions from the production of two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (96 to 99 percent silicon), and miscellaneous alloys (32 to 65 percent silicon) have been calculated.

Emissions from the production of ferrochromium and ferromanganese are not included because of the small number of manufacturers of these materials in the United States. Government information disclosure rules prevent the publication of production data for these production facilities. Additionally, production of ferrochromium in the United States ceased in 2009 (USGS 2013).

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon (FeSi) is given below:

$$\mathrm{Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7CO}$$

While most of the carbon contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Ferroalloys are used to alter the material properties of the steel. Ferroalloys are produced in conjunction with the iron and steel industry, often at co-located facilities, and production trends closely follow that of the iron and steel industry. As of 2018, 11 facilities in the United States produce ferroalloys (USGS 2021b). Emissions of CO_2 from ferroalloy production in 2020 were 1.4 MMT CO_2 Eq. (1,377 kt CO_2) (see Table 4-75 and Table 4-76), which is a 36

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[61] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2020 were 0.01 MMT CO_2 Eq. (0.4 kt CH_4), which is a 43 percent decrease since 1990. The decrease in emissions since 1990 can largely be attributed to two facility shutdowns in 2018 and one facility shutdown in 2020. Additionally, the COVID-19 pandemic and lower priced imported ferrosilicon had an impact on ferroalloy production in 2020 (USGS 2021a).

Table 4-75: CO_2 and CH_4 Emissions from Ferroalloy Production (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	2.2	1.4	1.8	2.0	2.1	1.6	1.4
CH_4	+	+	+	+	+	+	+
Total	**2.2**	**1.4**	**1.8**	**2.0**	**2.1**	**1.6**	**1.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Table 4-76: CO_2 and CH_4 Emissions from Ferroalloy Production (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	2,152	1,392	1,796	1,975	2,063	1,598	1,377
CH_4	1	+	1	1	1	+	+

+ Does not exceed 0.5 kt

Methodology and Time-Series Consistency

Emissions of CO_2 and CH_4 from ferroalloy production were calculated[62] using a Tier 1 method from the *2006 IPCC Guidelines* by multiplying annual ferroalloy production by material-specific default emission factors provided by IPCC (IPCC 2006). The Tier 1 equations for CO_2 and CH_4 emissions are as follows:

Equation 4-12: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions for Ferroalloy Production (Equation 4.15)

$$E_{CO_2} = \sum_i (MP_i \times EF_i)$$

where,

E_{CO2} = CO_2 emissions, metric tons
MP_i = Production of ferroalloy type *i*, metric tons
EF_i = Generic emission factor for ferroalloy type *i*, metric tons CO_2/metric ton specific ferroalloy product

Equation 4-13: *2006 IPCC Guidelines* Tier 1: CH_4 Emissions for Ferroalloy Production (Equation 4.18)

$$E_{CH_4} = \sum_i (MP_i \times EF_i)$$

where,

E_{CH4} = CH_4 emissions, kg
MP_i = Production of ferroalloy type *i*, metric tons
EF_i = Generic emission factor for ferroalloy type *i*, kg CH_4/metric ton specific ferroalloy product

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[62] EPA has not integrated aggregated facility-level GHGRP information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with production of ferroalloys did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

Default emission factors were used because country-specific emission factors are not currently available. The following emission factors were used to develop annual CO_2 and CH_4 estimates:

- Ferrosilicon, 25 to 55 percent Si and Miscellaneous Alloys, 32 to 65 percent Si: 2.5 metric tons CO_2/metric ton of alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Ferrosilicon, 56 to 95 percent Si: 4.0 metric tons CO_2/metric ton alloy produced, 1.0 kg CH_4/metric ton of alloy produced.
- Silicon Metal: 5.0 metric tons CO_2/metric ton metal produced, 1.2 kg CH_4/metric ton metal produced.

It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke in an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite carbon inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent carbon (C) and 10 percent inert material (Onder and Bagdoyan 1993).

The use of petroleum coke for ferroalloy production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRF Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Ferroalloy production data for 1990 through 2020 (see Table 4-77) were obtained from the U.S. Geological Survey (USGS) through the *Minerals Yearbook: Silicon* (USGS 1996 through 2013, 2021c) and the *Mineral Industry Surveys: Silicon* (USGS 2014, 2015, 2016b, 2017, 2018b, 2019, 2020). The following data were available from the USGS publications for the time series:

- Ferrosilicon, 25 to 55 percent Si: Annual production data were available from 1990 through 2010.
- Ferrosilicon, 56 to 95 percent Si: Annual production data were available from 1990 through 2010.
- Silicon Metal: Annual production data were available from 1990 through 2005. Production data for 2005 were used as estimates for 2006 through 2010 because data for these years were not available due to government information disclosure rules.
- Miscellaneous Alloys, 32 to 65 percent Si: Annual production data were available from 1990 through 1998. Starting 1999, USGS reported miscellaneous alloys and ferrosilicon containing 25 to 55 percent silicon as a single category.

Starting with the 2011 publication, USGS ceased publication of production quantity by ferroalloy product and began reporting all the ferroalloy production data as a single category (i.e., Total Silicon Materials Production). This is due to the small number of ferroalloy manufacturers in the United States and government information disclosure rules. Ferroalloy product shares developed from the 2010 production data (i.e., ferroalloy product production/total ferroalloy production) were used with the total silicon materials production quantity to estimate the production quantity by ferroalloy product type for 2011 through 2020 (USGS 2017, 2018b, 2019, 2020, 2021c).

Table 4-77: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%-55%	Ferrosilicon 56%-95%	Silicon Metal	Misc. Alloys 32-65%
1990	321,385	109,566	145,744	72,442
2005	123,000	86,100	148,000	NA
2016	165,282	145,837	159,881	NA
2017	181,775	160,390	175,835	NA
2018	189,846	167,511	183,642	NA
2019	147,034	129,736	142,229	NA
2020	126,681	111,778	122,541	NA

NA (Not Available) for product type, aggregated along with ferrosilicon (25-55% Si)

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

Annual ferroalloy production was reported by the USGS in three broad categories until the 2010 publication: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal (through 2005 only, 2005 value used as an estimate for 2006 through 2010). Starting with the *2011 Minerals Yearbook*, USGS started reporting all the ferroalloy production under a single category: total silicon materials production. The total silicon materials quantity was allocated across the three categories, based on the 2010 production shares for the three categories. Refer to the Methodology section for further details. Additionally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing proprietary company data. Emissions from this production category, therefore, were not estimated.

Some ferroalloys may be produced using wood or other biomass as a primary or secondary carbon source (carbonaceous reductants); however, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not be counted under this source because wood-based carbon is of biogenic origin.[63] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available, and are also often considered confidential business information.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging would reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-78. Ferroalloy production CO_2 emissions from 2020 were estimated to be between 1.2 and 1.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 13 percent above the emission estimate of 1.4 MMT CO_2 Eq. Ferroalloy production CH_4 emissions were estimated to be between a range of approximately 12 percent below and 13 percent above the emission estimate of 0.01 MMT CO_2 Eq.

Table 4-78: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.4	1.2	1.6	-13%	+13%
Ferroalloy Production	CH_4	+	+	+	-12%	+13%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

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[63] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

Pending available resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC procedures for the Ferroalloy Production source category. Given the small number of facilities and reporting thresholds, particular attention will be made to ensure completeness and time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[64] This is a long-term planned improvement, and EPA is still assessing the possibility of incorporating this improvement into the Inventory. This improvement has not been included in the current Inventory report.

4.19 Aluminum Production (CRF Source Category 2C3)

Aluminum is a lightweight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of recent reporting, the United States was the ninth[65] largest producer of primary aluminum, with approximately 1.5 percent of the world total production (USGS 2020). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of carbon dioxide (CO_2) and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

Carbon dioxide is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Héroult reduction process. The reduction of the alumina occurs through electrolysis in a molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a carbon (C) lining that serves as the cathode. Carbon is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 1.7 MMT CO_2 Eq. (1,748 kt) in 2020 (see Table 4-79). The C anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is

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[64] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

[65] Based on the U.S. USGS (2020) Aluminum factsheet, assuming all countries grouped under the "other countries" categories all have lower production than the U.S. Available at: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-aluminum.pdf

considered to be a non-energy use of petroleum coke and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here.

Table 4-79: CO_2 Emissions from Aluminum Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	6.8	6,831
2005	4.1	4,142
2016	1.3	1,334
2017	1.2	1,205
2018	1.5	1,451
2019	1.9	1,880
2020	1.7	1,748

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed High Voltage Anode Effects (HVAEs) HVAEs cause C from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given smelter and level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase. Another type of anode effect, Low Voltage Anode Effects (LVAEs), became a concern in the early 2010s as the aluminum industry increasingly began to use cell technologies with higher amperage and additional anodes (IPCC 2019). LVAEs emit CF_4 and are included in PFC emission totals from 2006 forward.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 92 percent to 1.4 MMT CO_2 Eq. of CF_4 (0.2 kt) and 0.3 MMT CO_2 Eq. of C_2F_6 (0.02 kt) in 2020, respectively, as shown in Table 4-80 and Table 4-81. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. These actions include technology and operational changes such as employee training, use of computer monitoring, and changes in alumina feeding techniques. Since 1990, aluminum production has declined by 75 percent, while the combined CF_4 and C_2F_6 emission rate (per metric ton of aluminum produced) has been reduced by 69 percent. PFC emissions decreased by approximately 5 percent between 2019 and 2020 due to decreases in aluminum production in 2020 for multiple factors, including shutdowns and economic (supply chain) disruptions from the COVID-19 pandemic.

Table 4-80: PFC Emissions from Aluminum Production (MMT CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	17.9	3.5	**21.5**
2005	2.9	0.6	**3.4**
2016	1.0	0.4	**1.4**
2017	0.7	0.4	**1.1**
2018	1.2	0.4	**1.6**
2019	1.4	0.4	**1.8**
2020	1.4	0.3	**1.7**

Note: Totals may not sum due to independent rounding.

Table 4-81: PFC Emissions from Aluminum Production (kt)

Year	CF_4	C_2F_6
1990	2.4	0.29
2005	0.4	0.05
2016	0.1	0.04
2017	0.1	0.03
2018	0.2	0.03
2019	0.2	0.03
2020	0.2	0.02

In 2020, U.S. primary aluminum production totaled approximately 1.012 million metric tons, a 4 percent decrease from 2019 production levels (USGS 2021). In 2020, three companies managed production at seven operational primary aluminum smelters in six states. Two smelters operated at full capacity during 2020, while four smelters operated at reduced capacity (USGS 2021). One smelter operated at reduced capacity until it was idled in July. Domestic smelters were operating at about 49 percent of capacity of 1.79 million tons per year at year end 2020 (USGS 2021).

The COVID-19 pandemic impacted domestic aluminum production and imports indirectly and directly, and neither USGS nor USAA sources have stated projections for the production year 2021.

Methodology and Time-Series Consistency

Process CO_2 and PFC (i.e., CF_4 and C_2F_6) emission estimates from primary aluminum production for 2010 through 2020 are available from EPA's GHGRP Subpart F (Aluminum Production) (EPA 2021). Under EPA's GHGRP, facilities began reporting primary aluminum production process emissions (for 2010) in 2011; as a result, GHGRP data (for 2010 through 2020) are available to be incorporated into the Inventory. EPA's GHGRP mandates that all facilities that contain an aluminum production process must report: CF_4 and C_2F_6 emissions from anode effects in all prebake and Søderberg electrolysis cells, CO_2 emissions from anode consumption during electrolysis in all prebake and Søderberg cells, and all CO_2 emissions from onsite anode baking. To estimate the process emissions, EPA's GHGRP uses the process-specific equations detailed in Subpart F (aluminum production).[66] These equations are based on the Tier 2/Tier 3 IPCC (2006) methods for primary aluminum production, and Tier 1 methods when estimating missing data elements. It should be noted that the same methods (i.e., *2006 IPCC Guidelines*) were used for estimating the emissions prior to the availability of the reported GHGRP data in the Inventory. Prior to 2010, aluminum production data were provided through EPA's Voluntary Aluminum Industrial Partnership (VAIP).

As previously noted, the use of petroleum coke for aluminum production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion [CRF Source Category 1A]) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Process CO_2 Emissions from Anode Consumption and Anode Baking

Carbon dioxide emission estimates for the years prior to the introduction of EPA's GHGRP in 2010 were estimated using *2006 IPCC Guidelines* methods, but individual facility reported data were combined with process-specific

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[66] Code of Federal Regulations, Title 40: Protection of Environment, Part 98: Mandatory Greenhouse Gas Reporting, Subpart F—Aluminum Production. See https://www.ecfr.gov/cgi-bin/text-idx?SID=24a41781dfe4218b339e914de03e8727&mc=true&node=pt40.23.98&rgn=div5#sp40.23.98.f.

emissions modeling. These estimates were based on information previously gathered from EPA's Voluntary Aluminum Industrial Partnership (VAIP) program, U.S. Geological Survey (USGS) Mineral Commodity reviews, and The Aluminum Association (USAA) statistics, among other sources. Since pre- and post-GHGRP estimates use the same methodology, emission estimates are comparable across the time series.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters.

Depending on the availability of smelter-specific data, the CO_2 emitted from electrolysis at each smelter was estimated from: (1) the smelter's annual anode consumption, (2) the smelter's annual aluminum production and rate of anode consumption (per ton of aluminum produced) for previous and/or following years, or (3) the smelter's annual aluminum production and IPCC default CO_2 emission factors. The first approach tracks the consumption and carbon content of the anode, assuming that all C in the anode is converted to CO_2. Sulfur, ash, and other impurities in the anode are subtracted from the anode consumption to arrive at a C consumption figure. This approach corresponds to either the IPCC Tier 2 or Tier 3 method, depending on whether smelter-specific data on anode impurities are used. The second approach interpolates smelter-specific anode consumption rates to estimate emissions during years for which anode consumption data are not available. This approach avoids substantial errors and discontinuities that could be introduced by reverting to Tier 1 methods for those years. The last approach corresponds to the IPCC Tier 1 method (IPCC 2006) and is used in the absence of present or historic anode consumption data.

The equations used to estimate CO_2 emissions in the Tier 2 and 3 methods vary depending on smelter type (IPCC 2006). For Prebake cells, the process formula accounts for various parameters, including net anode consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, the formula accounts for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. For Søderberg cells, the process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, anode consumption (and some anode impurity) data have been reported for 1990, 2000, 2003, 2004, 2005, 2006, 2007, 2008, and 2009. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003 and 2004, 14 out of 15 operating smelters in 2005, 13 out of 14 operating smelters in 2006, 5 out of 14 operating smelters in 2007 and 2008, and 3 out of 13 operating smelters in 2009. For years where CO_2 emissions data or CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming representative (e.g., previously reported or industry default) values.

In the absence of any previous historical smelter-specific process data (i.e., 1 out of 13 smelters in 2009; 1 out of 14 smelters in 2006, 2007, and 2008; 1 out of 15 smelters in 2005; and 5 out of 23 smelters between 1990 and 2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Process PFC Emissions from Anode Effects

High Voltage Anode Effects

Smelter-specific PFC emissions from aluminum production for 2010 through 2020 were reported to EPA under its GHGRP. To estimate their PFC emissions from HVAEs and report them under EPA's GHGRP, smelters use an approach identical to the Tier 3 approach in the *2006 IPCC Guidelines* (IPCC 2006). Specifically, they use a smelter-specific slope coefficient as well as smelter-specific operating data to estimate an emission factor using the following equation:

$$PFC = S \times AE$$

$$AE = F \times D$$

where,

PFC = CF_4 or C_2F_6, kg/MT aluminum
S = Slope coefficient, PFC/AE
AE = Anode effect, minutes/cell-day
F = Anode effect frequency per cell-day
D = Anode effect duration, minutes

They then multiply this emission factor by aluminum production to estimate PFC emissions from HVAEs. All U.S. aluminum smelters are required to report their emissions under EPA's GHGRP.

Perfluorocarbon emissions for the years prior to 2010 were estimated using the same equation, but the slope-factor used for some smelters was technology-specific rather than smelter-specific, making the method a Tier 2 rather than a Tier 3 approach for those smelters. Emissions and background data were reported to EPA under the VAIP. For 1990 through 2009, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 94 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC technology-specific slope coefficients were applied (IPCC 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP to estimate emission factors over time. For 1990 through 2009, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, representative values (e.g., previously reported or industry averages) were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2009, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS or USAA, and then allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions.

Table 4-82: Summary of HVAE Emissions

Year	MMT CO_2 Eq.
1990	21.5
2005	3.4
2016	1.4
2017	1.0
2018	1.6
2019	1.7
2020	1.6

Low Voltage Anode Effects

LVAE emissions of CF_4 were estimated for 2006 through 2020 based on the Tier 1 (technology-specific, production-based) method in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019). Prior to 2006, LVAE emissions are believed to have been negligible.[67] The following equation was used to estimate LVAE PFC emissions:

Equation 4-14: CF_4 Emissions Resulting from Low Voltage Anode Effects

$$LVAE\ E_{CF4} = LVAE\ EF_{CF4} \times MP$$

where,

$LVAE\ E_{CF4}$ = LVAE emissions of CF_4 from aluminum production, kg CF_4
$LVAE\ EF_{CF4}$ = LVAE emission factor for CF_4 (default by cell technology type)
MP = metal production by cell technology type, tons Al.

Once LVAE emissions were estimated, they were then combined with HVAE emissions estimates to calculate total PFC emissions from aluminum production.

Table 4-83: Summary of LVAE Emissions

Year	MMT CO_2 Eq.
2006	0.1
2016	0.1
2017	0.1
2018	0.1
2019	0.1
2020	0.1

Production Data

Between 1990 and 2009, production data were provided under the VAIP by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on the difference between reporting smelters and national aluminum production levels as reported to USGS, with allocation to specific smelters based on reported production capacities (USGS 1990 through 2009).

National primary aluminum production data for 2020, 2019, and 2018 were obtained via the 2020 USGS Mineral Industry Surveys, and the 2021 USGS Mineral Commodity Summaries. For 1990 through 2001, and 2006 (see Table 4-84) data were obtained from USGS *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002, 2007). For 2002 through 2005, and 2007 through 2017, national aluminum production data were obtained from the USAA's *Primary Aluminum Statistics* (USAA 2004 through 2006, 2008 through 2017).

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[67] The *2019 Refinement* states, "Since 2006, the global aluminum industry has undergone changes in technology and operating conditions that make LVAE emissions much more prevalent[12]; these changes have occurred not only through uptake of newer technologies (e.g., $PFPB_L$ to $PFPB_M$) but also during upgrades within the same technology in order to maximize productivity and reduce energy use" (IPCC 2019). Footnote #12 uses the example of $PFPB_L$, which is prevalent in the United States, as an older technology that has been upgraded.

Table 4-84: Production of Primary Aluminum (kt)

Year	kt
1990	4,048
2005	2,478
2016	818
2017	741
2018	891
2019	1,093
2020	1,012

Methodological approaches were applied to the entire time-series to ensure time-series consistency from 1990 through 2020.

Uncertainty

Uncertainty was estimated for the CO_2, CF_4, and C_2F_6 emission values reported by each individual facility to EPA's GHGRP, taking into consideration the uncertainties associated with aluminum production, anode effect minutes, and slope factors. The uncertainty bounds used for these parameters were established based on information collected under the VAIP and held constant through 2020. Uncertainty surrounding the reported CO_2, CF_4, and C_2F_6 emission values were determined to have a normal distribution with uncertainty ranges of approximately 6 percent below to 6 percent above, 16 percent below to 16 percent above, and 20 percent below to 20 percent above their 2020 emission estimates, respectively.

For LVAE, since emission values were not reported through EPA's GHGRP but estimated instead through a Tier 1 methodology, the uncertainty analysis examined uncertainty associated with primary capacity data as well as technology-specific emission factors. Uncertainty for each facility's primary capacity, reported in the USGS Yearbook, was estimated to have a Pert Beta distribution with an uncertainty range of 10 percent below to 7 percent above the capacity estimates based on the uncertainty of reported capacity data, the number of years since the facility reported new capacity data, and uncertainty in capacity utilization. Uncertainty was applied to LVAE emission factors according to technology using the uncertainty ranges provided in the *2019 Refinement to the 2006 IPCC Guidelines*. An uncertainty range for Horizontal Stud Søderberg (HSS) technology was not provided in the *2019 Refinement to the 2006 IPCC Guidelines* due to insufficient data, so a normal distribution and uncertainty range of ±99 percent was applied for that technology based on expert judgment. A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2, CF_4, and C_2F_6 emission estimates for the U.S. aluminum industry as a whole, and the results are provided below.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-85. Aluminum production-related CO_2 emissions were estimated to be between 1.71 and 1.79 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 2 percent below to 2 percent above the emission estimate of 1.75 MMT CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 1.29 and 1.50 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below to 8 percent above the emission estimate of 1.39 MMT CO_2 Eq. Aluminum production-related C_2F_6 emissions were estimated to be between 0.25 and 0.32 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 11 percent below to 11 percent above the emission estimate of 0.29 MMT CO_2 Eq. Finally, Aluminum production-related aggregated PFCs emissions were estimated to be between 1.57 and 1.79 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 6 percent below to 7 percent above the emission estimate of 1.68 MMT CO_2 Eq.

Table 4-85: Approach 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	1.75	1.71	1.79	-2%	2%
Aluminum Production	CF_4	1.39	1.29	1.50	-7%	8%
Aluminum Production	C_2F_6	0.29	0.25	0.32	-11%	11%
Aluminum Production	PFCs	1.68	1.57	1.79	-6%	7%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[68] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

In the LVAE emissions calculations, the Metal Production (MP) factor is calculated differently for the years 2006 through 2009 than for 2010 and beyond. For years prior to GHGRP reporting (2006 through 2009), the MP factor is calculated by dividing the annual production reported by USAA with the total U.S. capacity reported for this specific year, based on the USGS yearbook. For GHGRP reporting years (2010+), the methodology to calculate the MP value was changed to allocate the total annual production reported by USAA, based on the distribution of CO_2 emissions amongst the operating smelters in a specific year. The latter improves the accuracy of the LVAE emissions estimates over assuming capacity utilization is the same at all smelters. The main drawback of using this methodology to calculate the MP factor is that, in some instances, it led to production estimates that are slightly larger (<6 percent) than the production capacity reported that year. In practice, this is most likely explained by the degree of uncertainty in the USAA annual production reporting, and the differences in process efficiencies, measurements and methods used by each facility to obtain the CO_2, which cannot be completely homogenized throughout the reporting facilities.

Following Expert review comments, the total primary aluminum production estimates were updated to reflect data reported to the USGS (as detailed in Production Data section above) for the year 2018, 2019 and 2020, whereas previously, production estimates from the U.S. Aluminum Association were used for these specific years. The data from USGS are compiled from the U.S. Geological Survey monthly surveys sent to the primary aluminum smelters owned by the companies operating in the United States. In these recent years, all companies, who were sent the surveys, responded, thus making USGS data the most accurate available. These data source modifications did not lead to differences in the greenhouse gas emissions calculations for these specific years.

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[68] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

Planned Improvements

EPA will further investigate the sources of historical total primary aluminum production estimates for the earlier years in the timeseries and potentially update historical estimates to aim for increased consistency throughout the timeseries. As part of this planned improvement, EPA will review whether historical estimates are broken down into smelter specific production estimates, which are the basis for calculating smelter PFC (for non-partners) and CO_2 emissions (for all facilities) for the 1990 through 2009 time series (years preceding GHGRP reporting).

4.20 Magnesium Production and Processing (CRF Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. Sulfur hexafluoride has been used in this application around the world for more than thirty years. A dilute gaseous mixture of SF_6 with dry air and/or carbon dioxide (CO_2) is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF_6 reacting in magnesium production and processing is considered to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Alternative cover gases, such as AM-cover™ (containing HFC-134a), Novec™ 612 (FK-5-1-12) and dilute sulfur dioxide (SO_2) systems can and are being used by some facilities in the United States. However, many facilities in the United States are still using traditional SF_6 cover gas systems. Carbon dioxide is also released during primary magnesium production if carbonate based raw materials, such as dolomite, are used. During the processing of these raw materials to produce magnesium, calcination occurs which results in a release of CO_2 emissions.

The magnesium industry emitted 0.9 MMT CO_2 Eq. (0.04 kt) of SF_6, 0.1 MMT CO_2 Eq. (0.04 kt) of HFC-134a, and 0.001 MMT CO_2 Eq. (0.9 kt) of CO_2 in 2020. This represents a decrease of approximately 2 percent from total 2019 emissions (see Table 4-86 and Table 4-87) and a decrease in SF_6 emissions by 1 percent. In 2020, total HFC-134a emissions decreased from 0.066 MMT CO_2 Eq. to 0.058 MMT CO_2 Eq., or a 13 percent decrease as compared to 2019 emissions. FK 5-1-12 emissions in 2020 were consistent with 2019. The emissions of the carrier gas, CO_2, decreased from 1.40 kt in 2019 to 0.94 kt in 2020, or 33 percent. These decreases are likely attributed to decreasing production levels between 2019 and 2020. For the first time this year CO_2 emissions from the use of dolomite in primary production are included under Magnesium Production and Processing. Previously, these emissions had been included under Other Process Uses of Carbonates. This inclusion resulted in a significant increase in CO_2 emissions from 1990 through 2001, the time period during which it is known that dolomite was used in primary production, as compared to previously compiled Inventories. Additional information related to this update is provided below.

Table 4-86: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
SF_6	5.2	2.7	1.1	1.0	1.0	0.9	0.9
HFC-134a	0.0	0.0	0.1	0.1	0.1	0.1	0.1
CO_2	0.1	+	+	+	+	+	+
FK 5-1-12[a]	*0.0*	*0.0*	*+*	*+*	*+*	*+*	*+*
Total	**5.3**	**2.7**	**1.2**	**1.1**	**1.1**	**0.9**	**0.9**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Emissions of FK 5-1-12 are not included in totals.

Table 4-87: SF_6, HFC-134a, FK 5-1-12 and CO_2 Emissions from Magnesium Production and Processing (kt)

Year	1990		2005		2016	2017	2018	2019	2020
SF_6	0.2		0.1		+	+	+	+	+
HFC-134a	0.0		0.0		0.1	0.1	0.1	+	+
CO_2	128.5		3.3		2.8	3.3	1.6	1.4	0.9
FK 5-1-12 [a]	*0.0*		*0.0*		+	+	+	+	+

+ Does not exceed 0.05 kt

[a] Emissions of FK 5-1-12 are not included in totals.

Methodology and Time-Series Consistency

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry as well as emissions data reported through Subpart T (Magnesium Production and Processing) of EPA's GHGRP. The Partnership started in 1999 and, in 2010, participating companies represented 100 percent of U.S. primary and secondary production and 16 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). SF_6 emissions for 1999 through 2010 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. Partners reported their SF_6 consumption, which is assumed to be equivalent to emissions. Along with SF_6, some Partners reported their HFC-134a and FK 5-1-12 consumed, which is also assumed to be equal to emissions. The last reporting year under the Partnership was 2010. Emissions data for 2011 through 2020 are obtained through EPA's GHGRP. Under the program, owners or operators of facilities that have a magnesium production or casting process must report emissions from use of cover or carrier gases, which include SF_6, HFC-134a, FK 5-1-12 and CO_2. Consequently, cover and carrier gas emissions from magnesium production and processing were estimated for three time periods, depending on the source of the emissions data: 1990 through 1998 (pre-EPA Partnership), 1999 through 2010 (EPA Partnership), and 2011 through 2020 (EPA GHGRP). The methodologies described below also make use of magnesium production data published by the U.S. Geological Survey (USGS) as available.

1990 through 1998

To estimate emissions for 1990 through 1998, industry SF_6 emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. For this period, it was assumed that there was no use of HFC-134a or FK 5-1-12 cover gases, and hence emissions were not estimated for these alternatives.

Sulfur hexafluoride emission factors from 1990 through 1998 were based on a number of sources and assumptions. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995. The primary production emission factors were 1.2 kg SF_6 per metric ton for 1990 through 1993, and 1.1 kg SF_6 per metric ton for 1994 through 1997. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average Partner value. An emission factor for die casting of 4.1 kg SF_6 per metric ton, which was available for the mid-1990s from an international survey (Gjestland and Magers 1996), was used for years 1990 through 1996. For 1996 through 1998, the emission factor for die casting was assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that was reported in the RAND survey of major SF_6 manufacturers, which showed a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 1990 through 2001 were assumed to be the same as the 2002 emission factor. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-86. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

The quantities of CO_2 carrier gas used for each production type have been estimated using the 1999 estimated CO_2 emissions data and the annual calculated rate of change of SF_6 use in the 1990 through 1999 time period. For each year and production type, the rate of change of SF_6 use between the current year and the subsequent year was first estimated. This rate of change was then applied to the CO_2 emissions of the subsequent year to determine the CO_2 emission of the current year.

Carbon dioxide emissions from the calcination of dolomite in the primary production of magnesium were calculated based on the *2006 IPCC Guidelines* Tier 2 method by multiplying the estimated primary production of magnesium by an emissions factor of 3.62 kilogram of CO_2 per kilogram of magnesium produced.[69] For 1990 through 1998, production was estimated to be equal to the production capacity of the facility.

1999 through 2010

The 1999 through 2010 emissions from primary and secondary production were based on information provided by EPA's industry Partners. In some instances, there were years of missing Partner data, including SF_6 consumption and metal processed. For these situations, emissions were estimated through interpolation where possible, or by holding company-reported emissions (as well as production) constant from the previous year. For alternative cover gases, including HFC-134a and FK 5-1-12, mainly reported data was relied upon. That is, unless a Partner reported using an alternative cover gas, it was not assumed it was used. Emissions of alternate gases were also estimated through linear interpolation where possible.

The die casting emission estimates for 1999 through 2010 were also based on information supplied by industry Partners. When a Partner was determined to be no longer in production, its metal production and usage rates were set to zero. Missing data on emissions or metal input was either interpolated or held constant at the last available reported value. In 1999 through 2010, Partners were assumed to account for all die casting tracked by USGS. For 1999, die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emission estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. This emission factor was developed using magnesium production and SF_6 usage data for the year 1999. In 2008, the derived emission factor for die casting began to increase after many years of largely decreasing emission factors. As determined through an analysis of activity data reported from the USGS, this increase is due to a temporary decrease in production at many facilities between 2008 and 2010, which reflects the change in production that occurred during the recession.

The emissions from other casting operations were estimated by multiplying emission factors (kg SF_6 per metric ton of metal produced or processed) by the amount of metal produced or consumed from USGS, with the exception of some years for which Partner sand casting emissions data are available. The emission factors for sand casting activities were acquired through the data reported by the Partnership for 2002 to 2006. For 1999 through 2001, the sandcasting emission factor was held constant at the 2002 Partner-reported level. For 2007 through 2010, the sandcasting Partner did not report and the reported emission factor from 2005 was applied to the Partner and to all other sand casters. Activity data for 2005 was obtained from USGS (USGS 2005b).

The emission factors for primary production, secondary production and sand casting for the 1999 to 2010 are not published to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives. The emission factors for casting activities are provided below in Table 4-88.

The emissions of HFC-134a and FK-5-1-12 were included in the estimates for only instances where Partners reported that information to the Partnership. Emissions of these alternative cover gases were not estimated for instances where emissions were not reported.

Carbon dioxide carrier gas emissions were estimated using the emission factors developed based on GHGRP-reported carrier gas and cover gas data, by production type. It was assumed that the use of carrier gas, by production type, is proportional to the use of cover gases. Therefore, an emission factor, in kg CO_2 per kg cover gas

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[69] See https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_4_Ch4_Metal_Industry.pdf.

and weighted by the cover gases used, was developed for each of the production types. GHGRP data, on which these emissions factors are based, was available for primary, secondary, die casting and sand casting. The emission factors were applied to the quantity of all cover gases used (SF_6, HFC-134a, and FK-5-1-12) by production type in this time period for producers that reported CO_2 emissions from 2011-2020 through the GHGP. Carrier gas emissions for the 1999 through 2010 time period were only estimated for those Partner companies that reported using CO_2 as a carrier gas through the GHGRP. Using this approach helped ensure time-series consistency. Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using the ratio of total CO_2 emissions to total cover gas emissions for primary, secondary, die and sand in a given year and the total SF_6 emissions from each permanent mold, wrought, and anodes processes respectively in that same year. CO_2 emissions from the calcination of dolomite were estimated using the same approach as described above. At the end of 2001, the sole magnesium production plant operating in the United States that produced magnesium metal using a dolomitic process that resulted in the release of CO_2 emissions ceased its operations (USGS 1995b through 2020).

Table 4-88: SF_6 Emission Factors (kg SF_6 per metric ton of magnesium)

Year	Die Casting[a]	Permanent Mold	Wrought	Anodes
1999	1.75[b]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.79	2	1	1
2005	0.77	2	1	1
2006	0.88	2	1	1
2007	0.64	2	1	1
2008	0.97	2	1	1
2009	1.41	2	1	1
2010	1.43	2	1	1

[a] Weighted average includes all die casters, Partners and non-Partners. For the majority of the time series (2000 through 2010), Partners made up 100 percent of die casters in the United States.

[b] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

2011 through 2020

For 2011 through 2020, for the primary and secondary producers, GHGRP-reported cover and carrier gases emissions data were used. For sand and die casting, some emissions data was obtained through EPA's GHGRP. Additionally, in 2018 a new GHGRP reporter began reporting permanent mold emissions. The balance of the emissions for this industry segment was estimated based on previous Partner reporting (i.e., for Partners that did not report emissions through EPA's GHGRP) or were estimated by multiplying emission factors by the amount of metal produced or consumed. Partners who did not report through EPA's GHGRP were assumed to have continued to emit SF_6 at the last reported level, which was from 2010 in most cases, unless publicly available sources indicated that these facilities have closed or otherwise eliminated SF_6 emissions from magnesium production (ARB 2015). Many Partners that did report through the GHGRP showed increases in SF_6 emissions driven by increased production related to a continued economic recovery after the 2008 recession. One Partner in particular reported an anonymously large increase in SF_6 emissions from 2010 to 2011, further driving increases in emissions between the two time periods of inventory estimates. All Partners were assumed to have continued to consume magnesium at the last reported level. Where the total metal consumption estimated for the Partners fell below the U.S. total reported by USGS, the difference was multiplied by the emission factors discussed in the section above, i.e., non-partner emission factors. For the other types of production and processing (i.e., permanent mold, wrought, and anode casting), emissions were estimated by multiplying the industry emission factors with the metal production or consumption statistics obtained from USGS (USGS 2020). USGS data for 2020 were not yet available at the time of the analysis, so the 2019 values were held constant through 2020 as an estimate.

Emissions of carrier gases for permanent mold, wrought, and anode processes were estimated using an approach consistent with the 1999 through 2010 time series.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020. *2006 IPCC Guidance* methodologies were used throughout the timeseries, mainly either a Tier 2 or Tier 3 approach depending on available data. Additionally, in this Inventory, steps were taken to ensure time-series consistency for CO_2 emissions. These steps are further highlights in the recalculations discussion below.

Uncertainty

Uncertainty surrounding the total estimated emissions in 2020 is attributed to the uncertainties around SF_6, HFC-134a, and CO_2 emission estimates. To estimate the uncertainty surrounding the estimated 2020 SF_6 emissions from magnesium production and processing, the uncertainties associated with three variables were estimated: (1) emissions reported by magnesium producers and processors for 2020 through EPA's GHGRP, (2) emissions estimated for magnesium producers and processors that reported via the Partnership in prior years but did not report 2020 emissions through EPA's GHGRP, and (3) emissions estimated for magnesium producers and processors that did not participate in the Partnership or report through EPA's GHGRP. An uncertainty of 5 percent was assigned to the emissions (usage) data reported by each GHGRP reporter for all the cover and carrier gases (per the *2006 IPCC Guidelines*). If facilities did not report emissions data during the current reporting year through EPA's GHGRP, SF_6 emissions data were held constant at the most recent available value reported through the Partnership. The uncertainty associated with these values was estimated to be 30 percent for each year of extrapolation (per the *2006 IPCC Guidelines*). The uncertainty of the total inventory estimate remained relatively constant between 2019 and 2020.

Alternate cover gas and carrier gases data was set equal to zero if the facilities did not report via the GHGRP. For those industry processes that are not represented in the Partnership, such as permanent mold and wrought casting, SF_6 emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-89). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with die casting and sand casting activities utilized emission factors based on Partner reported data with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

Additional uncertainties exist in these estimates that are not addressed in this methodology, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Previous measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, the extent to which this technique is used in the United States is unknown.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-89. Total emissions associated with magnesium production and processing were estimated to be between 0.84 and 1.00 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the 2020 emission estimate of 0.92 MMT CO_2 Eq. The uncertainty estimates for 2020 are slightly higher to the uncertainty reported for 2019 in the previous Inventory. This increase in uncertainty is attributed to the increased uncertainty around the emissions data that was estimated for reporters that did not report in 2020 or, in some cases, dating back to 2010. The longer the time period for which EPA needs to estimate emissions the larger the associated uncertainty with those emission estimates will be.

Table 4-89: Approach 2 Quantitative Uncertainty Estimates for SF_6, HFC-134a and CO_2 Emissions from Magnesium Production and Processing (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6, HFC-134a, CO_2	0.92	0.84	1.00	-9%	9%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. Inventory QA/QC plan, which is in accordance with Volume 1, Chapter 6 of *2006 IPCC Guidelines* as described in the introduction of the IPPU chapter (see Annex 8 for more details). For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[70] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

Recalculations Discussion

Sand casting and permanent mold casting volumes were updated based on the release of an updated USGS Minerals Yearbook (USGS 2020). Primary production SF_6 emissions were set equal to zero from 2016 through 2020 because of a confirmation that the facility transitioned completed to HFC-134a in 2016. Additionally, one facility's reported GHGRP emissions were revised in 2017 due to additional information provided on emissions from HFC-134a and CO_2. Lastly, a correction was made for a die casting facility for 2016. This facility did not report in 2016 and previously 2016 SF_6 emissions were held constant at 2015 levels. This approach was updated to estimate 2016 SF_6 emissions through interpolation between 2015 and 2017.

Three changes were made in this Inventory in relation to CO_2 emissions. First, CO_2 emissions were added for permanent mold, wrought, and anode production throughout the time series. Second, it was discovered that CO_2 emissions from sand casting were not included from 1990 through 2010. These emissions were added in this Inventory. Lastly, CO_2 emissions from the use of dolomite in primary production from 1990 to 2001 are now reported under Magnesium Production and Processing instead of elsewhere in the inventory, which is consistent with the *2006 IPCC Guidelines*. The methods used to implement these changes are described above.

Planned Improvements

Cover gas research conducted over the last decade has found that SF_6 used for magnesium melt protection can have degradation rates on the order of 20 percent in die casting applications (Bartos et al. 2007). Current emission estimates assume (per the *2006 IPCC Guidelines*) that all SF_6 utilized is emitted to the atmosphere. Additional

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[70] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

research may lead to a revision of the *2006 IPCC Guidelines* to reflect this phenomenon and until such time, developments in this sector will be monitored for possible application to the Inventory methodology.

Additional emissions are generated as byproducts from the use of alternate cover gases, which are not currently accounted for. Research on this topic is developing, and as reliable emission factors become available, these emissions will be incorporated into the Inventory.

4.21 Lead Production (CRF Source Category 2C5)

In 2020, lead was produced in the United States only using secondary production processes. Until 2014, lead production in the United States involved both primary and secondary processes—both of which emit carbon dioxide (CO_2) (Sjardin 2003). Emissions from fuels consumed for energy purposes during the production of lead are accounted for in the Energy chapter.

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). Primary lead production, in the form of direct smelting, previously occurred at a single smelter in Missouri. This primary lead smelter was closed at the end of 2013. In 2014, the smelter processed a small amount of residual lead during demolition of the site (USGS 2015).

Similar to primary lead production, CO_2 emissions from secondary lead production result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process. Carbon dioxide emissions from secondary production also occur through the treatment of secondary raw materials (Sjardin 2003). Secondary production primarily involves the recycling of lead acid batteries and post-consumer scrap at secondary smelters. Secondary lead production has increased in the United States over the past decade, while primary lead production has decreased to production levels of zero. In 2020, secondary lead production accounted for 100 percent of total lead production. The lead-acid battery industry accounted for about 92 percent of the reported U.S. lead consumption in 2020 (USGS 2021).

In 2020, U.S. primary lead production remained at production levels of zero, and secondary lead production in the United States decreased by approximately 6 percent compared to 2019, due to the COVID-19 pandemic, the resulting quarantine-related restrictions, and a decrease in demand for lead (USGS 2021). Secondary lead production in 2020 is 19 percent higher than in 1990 (USGS 1994 and 2021). The United States has become more reliant on imported refined lead, owing to the closure of the last primary lead smelter in 2013. Exports of spent starting-lighting-ignition (SLI) batteries have been generally decreasing since 2014and were 12 percent lower in the first 9 months of 2020 compared to the same time period in 2014 (USGS 2015 through 2020). In the first 9 months of 2020, 19.7 million spent SLI lead-acid batteries were exported, slightly less than that in the same time period in 2019 (USGS 2021).

In 2020, U.S. lead production totaled 1,100,000 metric tons (USGS 2021). The resulting emissions of CO_2 from 2020 lead production were estimated to be 0.5 MMT CO_2 Eq. (495 kt) (see Table 4-90).

The United States was the third largest mine producer of lead in the world, behind China and Australia, and accounted for approximately 7 percent of world production in 2020 (USGS 2021).

Table 4-90: CO_2 Emissions from Lead Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.5	516
2005	0.6	553
2016	0.5	500
2017	0.5	513
2018	0.5	513
2019	0.5	527
2020	0.5	495

After a steady increase in total emissions from 1995 to 2000, total emissions decreased between 2000 and 2013 (8 percent decline across the time period), exhibited a single year decrease of 16 percent between 2013 and 2014, gradually increased between 2014 and 2019, and are currently 4 percent lower than 1990 levels.

Methodology and Time-Series Consistency

The methods used to estimate emissions for lead production[71] are based on Sjardin's work (Sjardin 2003) for lead production emissions and Tier 1 methods from the *2006 IPCC Guidelines*. The Tier 1 equation is as follows:

Equation 4-15: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Lead Production (Equation 4.32)

$$CO_2\ Emissions = (DS\ \times EF_{DS}) + (S\ \times EF_S)$$

where,

DS = Lead produced by direct smelting, metric ton
S = Lead produced from secondary materials
EF_{DS} = Emission factor for direct smelting, metric tons CO_2/metric ton lead product
EF_S = Emission factor for secondary materials, metric tons CO_2/metric ton lead product

For primary lead production using direct smelting, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead. For secondary lead production, Sjardin (2003) and the *2006 IPCC Guidelines* provide an emission factor of 0.25 metric tons CO_2/metric ton lead for direct smelting, as well as an emission factor of 0.2 metric tons CO_2/metric ton lead produced for the treatment of secondary raw materials (i.e., pretreatment of lead acid batteries). Since the secondary production of lead involves both the use of the direct smelting process and the treatment of secondary raw materials, Sjardin recommends an additive emission factor to be used in conjunction with the secondary lead production quantity. The direct smelting factor (0.25) and the sum of the direct smelting and pretreatment emission factors (0.45) are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The production and use of coking coal for lead production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

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[71] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Lead Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

The 1990 through 2020 activity data for primary and secondary lead production (see Table 4-91) were obtained from the U.S. Geological Survey (USGS 1995 through 2021).

Table 4-91: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
2005	143,000	1,150,000
2016	0	1,110,000
2017	0	1,140,000
2018	0	1,140,000
2019	0	1,170,000
2020	0	1,100,000

Methodological approaches discussed below were applied to applicable years to ensure time-series consistency in emissions from 1990 through 2020.

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averaged the values provided by three other studies (Dutrizac et al. 2000; Morris et al. 1983; Ullman 1997). For secondary production, Sjardin (2003) added a CO_2 emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS which is collected via voluntary surveys; the uncertainty of the activity data is a function of the reliability of reported plant-level production data and the completeness of the survey response.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-92. Lead production CO_2 emissions in 2020 were estimated to be between 0.4 and 0.6 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below and 16 percent above the emission estimate of 0.5 MMT CO_2 Eq.

Table 4-92: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lead Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO_2	0.5	0.4	0.6	-15%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Initial review of activity data show that EPA's GHGRP Subpart R lead production data and resulting emissions are fairly consistent with those reported by USGS. EPA is still reviewing available GHGRP data, reviewing QC analysis to understand differences in data reporting (i.e., threshold implications), and assessing the possibility of including this planned improvement in future Inventory reports (see Planned Improvements section below). Currently, GHGRP data are used for QA purposes only.

Recalculations Discussion

Emissions for 2019 were revised from 0.5 MMT CO_2 Eq. (540 kt) to 0.5 MMT CO_2 Eq. (527 kt) based on revised USGS data for secondary lead production.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Lead Production source category, in particular considering completeness of reported lead production given the reporting threshold. Particular attention will be made to ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[72]

4.22 Zinc Production (CRF Source Category 2C6)

Zinc production in the United States consists of both primary and secondary processes. Of the primary and secondary processes currently used in the United States, only the electrothermic and Waelz kiln secondary processes result in non-energy carbon dioxide (CO_2) emissions (Viklund-White 2000). Emissions from fuels consumed for energy purposes during the production of zinc are accounted for in the Energy chapter.

The majority of zinc produced in the United States is used for galvanizing. Galvanizing is a process where zinc coating is applied to steel in order to prevent corrosion. Zinc is used extensively for galvanizing operations in the automotive and construction industry. Zinc is also used in the production of zinc alloys and brass and bronze alloys (e.g., brass mills, copper foundries, and copper ingot manufacturing). Zinc compounds and dust are also used, to a lesser extent, by the agriculture, chemicals, paint, and rubber industries.

Production of zinc can be conducted with a range of pyrometallurgical (e.g., electrothermic furnace, Waelz kiln, flame reactor, batch retorts, Pinto process, and PIZO process) and hydrometallurgical (e.g., hydrometallurgical recovery, solvent recovery, solvent extraction-electrowinning, and electrolytic) processes. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003). Primary production in the United States is conducted through the electrolytic process, while secondary techniques include the electrothermic and Waelz kiln processes, as well as a range of other processes. Worldwide primary zinc production also employs a pyrometallurgical process using an Imperial Smelting Furnace; however, this process is not used in the United States (Sjardin 2003).

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[72] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

In the electrothermic process, roasted zinc concentrate and secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke is added to the electric retort furnace as a carbon-containing reductant. This concentration step, using metallurgical coke and high temperatures, reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process also generates non-energy CO_2 emissions.

$$ZnO + C \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 1)}$$

$$ZnO + CO \rightarrow Zn(gas) + CO_2 \qquad \text{(Reaction 2)}$$

In the Waelz kiln process, electric arc furnace (EAF) dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent (typically carbon-containing metallurgical coke). When kiln temperatures reach approximately 1,100 to 1,200 degrees Celsius, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. The use of carbon-containing metallurgical coke in a high-temperature fuming process results in non-energy CO_2 emissions. Through this process, approximately 0.33 metric tons of zinc is produced for every metric ton of EAF dust treated (Viklund-White 2000).

In the flame reactor process, a waste feed stream, which can include EAF dust, is processed in a high-temperature environment (greater than 2,000 °C) created by the combustion of natural gas or coal and oxygen-enriched air. Volatile metals, including zinc, are forced into the gas phase and drawn into a combustion chamber, where air is introduced and oxidation occurs. The metal oxide product is then collected in a dust collection system (EPA 1992).

In 2020, the only companies in the United States that used emissive technology to produce secondary zinc products were American Zinc Recycling (AZR) (formerly "Horsehead Corporation") and Steel Dust Recycling (SDR). PIZO Operating Company, LLC (PIZO) operated a secondary zinc production facility that processed EAF dust in Blytheville, AR from 2009 to 2012.

For AZR, EAF dust is recycled in Waelz kilns at their Calumet, IL; Palmerton, PA; Rockwood, TN; and Barnwell, SC facilities. The AZR facility in Beaumont, TX processed EAF dust via flame reactor from 1993 through 2009 (AZR 2021, Horsehead 2014). These Waelz kiln and flame reactor facilities produce intermediate zinc products (crude zinc oxide or calcine), most of which was transported to their Monaca, PA facility where the products were smelted into refined zinc using electrothermic technology. In April 2014, AZR permanently closed their Monaca smelter. This was replaced by their new facility in Mooresboro, NC in 2014.

The Mooresboro facility uses a hydrometallurgical process (i.e., solvent extraction with electrowinning technology) to produce zinc products, which is assumed to be non-emissive as described above. The current capacity of the new facility is 155,000 short tons. Production at the Mooresboro facility was idled in April 2016 and re-started in March 2020, with plans to be at full capacity by 2021 (Recycling Today 2020). Direct consumption of coal, coke, and natural gas were replaced with electricity consumption at the new Mooresboro facility. The new facility is reported to have significantly lower greenhouse gas and other air emissions than the Monaca smelter (Horsehead 2012b).

The Mooresboro facility uses leaching and solvent extraction (SX) technology combined with electrowinning, melting, and casting technology. In this process, Waelz Oxide (WOX) is first washed in water to remove soluble elements such as chlorine, potassium, and sodium, and then is leached in a sulfuric acid solution to dissolve the contained zinc creating a pregnant liquor solution (PLS). The PLS is then processed in a solvent extraction step in which zinc is selectively extracted from the PLS using an organic solvent creating a purified zinc-loaded electrolyte solution. The loaded electrolyte solution is then fed into the electrowinning process in which electrical energy is applied across a series of anodes and cathodes submerged in the electrolyte solution causing the zinc to deposit on the surfaces of the cathodes. As the zinc metal builds up on these surfaces, the cathodes are periodically harvested in order to strip the zinc from their surfaces (Horsehead 2015).

SDR recycles EAF dust into intermediate zinc products using Waelz kilns and sells the intermediate products to companies who smelt it into refined products.

Emissions of CO_2 from zinc production in 2020 were estimated to be 1.0 MMT CO_2 Eq. (1,008 kt CO_2) (see Table 4-93). All 2020 CO_2 emissions resulted from secondary zinc production processes. Emissions from zinc production in the United States have increased overall since 1990 due to a gradual shift from non-emissive primary production to emissive secondary production. In 2020, emissions were estimated to be 60 percent higher than they were in 1990. Emissions decreased 2 percent from 2019 levels. Due largely to the COVID-19 pandemic, a decrease in both the demand for zinc and zinc prices led to a decrease in global zinc mine production in most producing countries, including the United States. While total refined zinc production increased in 2020 due to the reopening of an idled secondary zinc refinery, consumption of refined zinc decreased in association with a decline in the U.S. steel industry as a result of the pandemic. (USGS 2021).

Table 4-93: CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	0.6	632
2005	1.0	1,030
2016	0.8	838
2017	0.9	900
2018	1.0	999
2019	1.0	1,026
2020	1.0	1,008

In 2020, United States primary and secondary refined zinc production were estimated to total 150,000 metric tons (USGS 2021) (see Table 4-94). Domestic zinc mine production decreased in 2020, owing partially to a decrease in production at the Red Dog Mine in Alaska and the closure of the Pend Oreille Mine in Washington State in July 2019. Primary zinc production (primary slab zinc) in 2018 is used as an estimate for 2019 and 2020 due to the lack of available data. Secondary zinc production in 2020 increased by 250 percent compared to 2019 and was largely influenced by the reopening of the idled AZR secondary zinc refinery in Mooresboro, NC in March 2020 (USGS 2021; AZP 2021). Secondary zinc production from the reopened facility was estimated by subtracting estimated primary zinc production from the total zinc production value obtained from the USGS *Minerals Yearbook: Zinc*.

Table 4-94: Zinc Production (Metric Tons)

Year	Primary	Secondary	Total
1990	262,704	95,708	**358,412**
2005	191,120	156,000	**347,120**
2016	111,000	15,000	**126,000**
2017	117,000	15,000	**132,000**
2018	101,000	15,000	**116,000**
2019	101,000	14,000	**115,000**
2020	101,000	49,000	**150,000**

Methodology and Time-Series Consistency

The methods used to estimate non-energy CO_2 emissions from zinc production[73] using the electrothermic primary production and Waelz kiln secondary production processes are based on Tier 1 methods from the *2006 IPCC Guidelines* (IPCC 2006). The Tier 1 equation used to estimate emissions from zinc production is as follows:

Equation 4-16: *2006 IPCC Guidelines* Tier 1: CO_2 Emissions From Zinc Production (Equation 4.33)

$$E_{CO2} = Zn \times EF_{default}$$

where,

E_{CO2} = CO_2 emissions from zinc production, metric tons
Zn = Quantity of zinc produced, metric tons
$EF_{default}$ = Default emission factor, metric tons CO_2/metric ton zinc produced

The Tier 1 emission factors provided by IPCC for Waelz kiln-based secondary production were derived from metallurgical coke consumption factors and other data presented in Vikland-White (2000). These coke consumption factors as well as other inputs used to develop the Waelz kiln emission factors are shown below. IPCC does not provide an emission factor for electrothermic processes due to limited information; therefore, the Waelz kiln-specific emission factors were also applied to zinc produced from electrothermic processes. Starting in 2014, refined zinc produced in the United States used hydrometallurgical processes and is assumed to be non-emissive.

For Waelz kiln-based production, IPCC recommends the use of emission factors based on EAF dust consumption, if possible, rather than the amount of zinc produced since the amount of reduction materials used is more directly dependent on the amount of EAF dust consumed. Since only a portion of emissive zinc production facilities consume EAF dust, the emission factor based on zinc production is applied to the non-EAF dust consuming facilities, while the emission factor based on EAF dust consumption is applied to EAF dust consuming facilities.

The Waelz kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced (i.e., 1.19 metric tons coke/metric ton zinc produced) (Viklund-White 2000), and the following equation:

Equation 4-17: Waelz Kiln CO_2 Emission Factor for Zinc Produced

$$EF_{Waelz\ Kiln} = \frac{1.19\ metric\ tons\ coke}{metric\ tons\ zinc} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{3.70\ metric\ tons\ CO_2}{metric\ tons\ zinc}$$

Refined zinc production levels for AZR's Monaca, PA facility (utilizing electrothermic technology) were available from the company for years 2005 through 2013 (Horsehead 2008, 2011, 2012, 2013, and 2014). The Monaca facility was permanently shut down in April 2014 and replaced by AZR's new facility in Mooresboro, NC. The new facility uses hydrometallurgical process to produce refined zinc products. Hydrometallurgical production processes are assumed to be non-emissive since no carbon is used in these processes (Sjardin 2003).

Metallurgical coke consumption for non-EAF dust consuming facilities for 1990 through 2004 were extrapolated using the percentage change in annual refined zinc production at secondary smelters in the United States, as provided by the U.S. Geological Survey (USGS) *Minerals Yearbook: Zinc* (USGS 1995 through 2006). Metallurgical coke consumption for 2005 through 2013 were based on the secondary zinc production values obtained from the Horsehead Corporation Annual Report Form 10-k: 2005 through 2008 from the 2008 10-k (Horsehead Corp 2009); 2009 and 2010 from the 2010 10-k (Horsehead Corp. 2011); 2011 from the 2011 10-k (Horsehead Corp. 2012a);

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[73] EPA has not integrated aggregated facility-level Greenhouse Gas Reporting Program (GHGRP) information to inform these estimates. The aggregated information (e.g., activity data and emissions) associated with Zinc Production did not meet criteria to shield underlying confidential business information (CBI) from public disclosure.

2012 from the 2012 10-k (Horsehead Corp. 2013); and 2013 from the 2013 10-k (Horsehead Corp. 2014). Metallurgical coke consumption levels for 2014 and later were zero due to the closure of the AZR (formerly "Horsehead Corporation") Monaca, PA electrothermic furnace facility. The secondary zinc produced values for each year were then multiplied by the 3.70 metric tons CO_2/metric ton zinc produced emission factor to develop CO_2 emission estimates for the AZR electrothermic furnace facility.

The Waelz kiln emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed (i.e., 0.4 metric tons coke/metric ton EAF dust consumed) (Viklund-White 2000), and the following equation:

Equation 4-18: Waelz Kiln CO_2 Emission Factor for EAF Dust Consumed

$$EF_{EAF\ Dust} = \frac{0.4\ metric\ tons\ coke}{metric\ tons\ EAF\ Dust} \times \frac{0.85\ metric\ tons\ C}{metric\ tons\ coke} \times \frac{3.67\ metric\ tons\ CO_2}{metric\ tons\ C} = \frac{1.24\ metric\ tons\ CO_2}{metric\ tons\ EAF\ Dust}$$

Metallurgical coke consumption for EAF dust consuming facilities for 1990 through 2020 were calculated based on the values of EAF dust consumed. The values of EAF dust consumed for AZR, SDR, and PIZO are explained below. The total amount of EAF dust consumed by AZR at their Waelz kilns was available from AZR (formerly "Horsehead Corporation") financial reports for years 2006 through 2015 (Horsehead 2007, 2008, 2010a, 2011, 2012a, 2013, 2014, 2015, and 2016) and from AZR for 2016, 2017, 2018, and 2019 (AZR 2020). EAF dust consumption for 2020 was not available at the time of publication and were estimated using 2019 values. The EAF dust consumption values for each year were then multiplied by the 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor to develop CO_2 emission estimates for AZR's Waelz kiln facilities.

The amount of EAF dust consumed by SDR and their total production capacity were obtained from SDR's facility in Alabama for the years 2011 through 2020 (SDR 2012, 2014, 2015, 2017, 2018, 2021). The SDR facility has been operational since 2008, underwent expansion in 2011 to include a second unit (operational since early- to mid-2012), and expanded its capacity again in 2017 (SDR 2018). Annual consumption data for SDR was not publicly available for the years 2008, 2009, and 2010. These data were estimated using data for AZR's Waelz kilns for 2008 through 2010 (Horsehead 2007, 2008, 2010a, 2010b, and 2011). Annual capacity utilization ratios were calculated using AZR's annual consumption and total capacity for the years 2008 through 2010. AZR's annual capacity utilization ratios were multiplied with SDR's total capacity to estimate SDR's consumption for each of the years, 2008 through 2010 (SDR 2013). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to SDR's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

PIZO's facility in Arkansas was operational from 2009 to 2012 (PIZO 2021). The amount of EAF dust consumed by PIZO's facility for 2009 through 2012 was not publicly available. EAF dust consumption for PIZO's facility for 2009 and 2010 were estimated by calculating annual capacity utilization of AZR's Waelz kilns and multiplying this utilization ratio by PIZO's total capacity (PIZO 2012). EAF dust consumption for PIZO's facility for 2011 through 2012 were estimated by applying the average annual capacity utilization rates for AZR and SDR (Grupo PROMAX) to PIZO's annual capacity (Horsehead 2012; SDR 2012; PIZO 2012). The 1.24 metric tons CO_2/metric ton EAF dust consumed emission factor was then applied to PIZO's estimated EAF dust consumption to develop CO_2 emission estimates for those Waelz kiln facilities.

The production and use of coking coal for zinc production is adjusted for within the Energy chapter as this fuel was consumed during non-energy related activities. Additional information on the adjustments made within the Energy sector for Non-Energy Use of Fuels is described in both the Methodology section of CO_2 from Fossil Fuel Combustion (3.1 Fossil Fuel Combustion (CRF Source Category 1A)) and Annex 2.1, Methodology for Estimating Emissions of CO_2 from Fossil Fuel Combustion.

Beginning with the 2017 USGS *Minerals Commodity Summary: Zinc*, United States primary and secondary refined zinc production were reported as one value, total refined zinc production. Prior to this publication, primary and secondary refined zinc production statistics were reported separately. For the current Inventory report, EPA sought expert judgment from the USGS mineral commodity expert to assess approaches for splitting total production into primary and secondary values. For years 2016 through 2020, only one facility produced primary zinc. Primary zinc produced from this facility was subtracted from the USGS 2016 to 2020 total zinc production statistic to estimate secondary zinc production for these years.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

The uncertainty associated with these estimates is two-fold, relating to activity data and emission factors used.

First, there is uncertainty associated with the amount of EAF dust consumed in the United States to produce secondary zinc using emission-intensive Waelz kilns. The estimate for the total amount of EAF dust consumed in Waelz kilns is based on (1) an EAF dust consumption value reported annually by AZR/Horsehead Corporation as part of its financial reporting to the Securities and Exchange Commission (SEC) and provided by AZR, and (2) an EAF dust consumption value obtained from the Waelz kiln facility operated in Alabama by Steel Dust Recycling LLC. Since actual EAF dust consumption information is not available for PIZO's facility (2009 through 2010) and SDR's facility (2008 through 2010), the amount is estimated by multiplying the EAF dust recycling capacity of the facility (available from the company's website) by the capacity utilization factor for AZR (which is available from Horsehead Corporation financial reports).The EAF dust consumption for PIZO's facility for 2011 through 2012 was estimated by multiplying the average capacity utilization factor developed from AZR and SDR's annual capacity utilization rates by PIZO's EAF dust recycling capacity. Therefore, there is uncertainty associated with the assumption used to estimate PIZO's annual EAF dust consumption values for 2009 through 2012 and SDR's annual EAF dust consumption values for 2008 through 2010.

Second, there is uncertainty associated with the emission factors used to estimate CO_2 emissions from secondary zinc production processes. The Waelz kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed as provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances. Data limitations prevented the development of emission factors for the electrothermic process. Therefore, emission factors for the Waelz kiln process were applied to both electrothermic and Waelz kiln production processes.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-95. Zinc production CO_2 emissions from 2020 were estimated to be between 0.8 and 1.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 19 percent below and 20 percent above the emission estimate of 1.0 MMT CO_2 Eq.

Table 4-95: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	1.0	0.8	1.2	-19%	+20%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

No recalculations were made impacting emissions for the 1990 through 2019 portion of the time series.

Planned Improvements

Pending resources and prioritization of improvements for more significant sources, EPA will continue to evaluate and analyze data reported under EPA's GHGRP that would be useful to improve the emission estimates and category-specific QC for the Zinc Production source category, in particular considering completeness of reported zinc production given the reporting threshold. Given the small number of facilities in the United States, particular attention will be made to risks for disclosing CBI and ensuring time-series consistency of the emissions estimates presented in future Inventory reports, consistent with IPCC and UNFCCC guidelines. This is required as the facility-level reporting data from EPA's GHGRP, with the program's initial requirements for reporting of emissions in calendar year 2010, are not available for all inventory years (i.e., 1990 through 2009) as required for this Inventory. In implementing improvements and integration of data from EPA's GHGRP, the latest guidance from the IPCC on the use of facility-level data in national inventories will be relied upon.[74] This is a long-term planned improvement, and EPA is still assessing the possibility of including this improvement in future Inventory reports.

4.23 Electronics Industry (CRF Source Category 2E)

The electronics industry uses multiple greenhouse gases in its manufacturing processes. In semiconductor manufacturing, these include long-lived fluorinated greenhouse gases used for plasma etching and chamber cleaning (CRF Source Category 2E1), fluorinated heat transfer fluids used for temperature control and other applications (CRF Source Category 2E4), and nitrous oxide (N_2O) used to produce thin films through chemical vapor deposition and in other applications (reported under CRF Source Category 2H3). Similar to semiconductor manufacturing, the manufacturing of micro-electro-mechanical systems (MEMS) devices (reported under CRF Source Category 2E5 Other) and photovoltaic (PV) cells (CRF Source Category 2E3) requires the use of multiple long-lived fluorinated greenhouse gases for various processes.

The gases most commonly employed in the electronics industry are trifluoromethane (hydrofluorocarbon (HFC)-23 or CHF_3), perfluoromethane (CF_4), perfluoroethane (C_2F_6), nitrogen trifluoride (NF_3), and sulfur hexafluoride (SF_6), although other fluorinated compounds such as perfluoropropane (C_3F_8) and perfluorocyclobutane (c-C_4F_8) are also used. The exact combination of compounds is specific to the process employed.

In addition to emission estimates for these seven commonly used fluorinated gases, this Inventory contains emissions estimates for N_2O and other HFCs and unsaturated, low-GWP PFCs including C_5F_8, C_4F_6, HFC-32, HFC-41, and HFC-134a. These additional HFCs and PFCs are emitted from etching and chamber cleaning processes in much smaller amounts, accounting for 0.02 percent of emissions (in CO_2 Eq.) from these processes.

For semiconductors, a single 300 mm silicon wafer that yields between 400 to 600 semiconductor products (devices or chips) may require more than 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film to selectively remove the desired portions of the film. The material removed as well as undissociated

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[74] See http://www.ipcc-nggip.iges.or.jp/public/tb/TFI_Technical_Bulletin_1.pdf.

fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. Plasma enhanced chemical vapor deposition (PECVD) chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere.

In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C_2F_6 is used in cleaning or etching, CF_4 is typically generated and emitted as a process byproduct. In some cases, emissions of the byproduct gas can rival or even exceed emissions of the input gas, as is the case for NF_3 used in remote plasma chamber cleaning, which often generates CF_4 as a byproduct.

Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

Nitrous oxide is used in manufacturing semiconductor devices to produce thin films by CVD and nitridation processes as well as for N-doping of compound semiconductors and reaction chamber conditioning (Doering 2000).

Liquid perfluorinated compounds are also used as heat transfer fluids (F-HTFs) for temperature control, device testing, cleaning substrate surfaces and other parts, and soldering in certain types of semiconductor manufacturing production processes. Leakage and evaporation of these fluids during use is a source of fluorinated gas emissions (EPA 2006). Unweighted F-HTF emissions consist primarily of perfluorinated amines, hydrofluoroethers, perfluoropolyethers (specifically, PFPMIEs), and perfluoroalkylmorpholines. One percent or less consist of HFCs, PFCs, and SF_6 (where PFCs are defined as compounds including only carbon and fluorine). With the exceptions of the hydrofluoroethers and most of the HFCs, all of these compounds are very long-lived in the atmosphere and have global warming potentials (GWPs) near 10,000.[75]

MEMS and photovoltaic cell manufacturing require thin film deposition and etching of material with a thickness of one micron or more, so the process is less intricate and complex than semiconductor manufacturing. The manufacturing process is different than semiconductors, but generally employs similar techniques. Like semiconductors, MEMS and photovoltaic cell manufacturers use fluorinated compounds for etching, cleaning reactor chambers, and temperature control. CF_4, SF_6, and the Bosch process (which consists of alternating steps of SF_6 and C_4F_8) are used to manufacture MEMS (EPA 2010). Photovoltaic cell manufacturing predominately uses $CF_{4,}$ to etch crystalline silicon wafers, and C_2F_6 or NF_3 during chamber cleaning after deposition of SiN_x films (IPCC 2006), although other F-GHGs may be used. Similar to semiconductor manufacturing, both MEMS and photovoltaic cell manufacturing use N_2O in depositing films and other manufacturing processes. MEMS and photovoltaic manufacturing may also employ HTFs for cooling process equipment (EPA 2010).

Emissions from all fluorinated greenhouse gases (including F-HTFs) and N_2O for semiconductors, MEMS and photovoltaic cells manducating are presented in Table 4-96 below for the years 1990, 2005, and the period 2016 to 2020. The rapid growth of the electronics industry and the increasing complexity (growing number of layers and functions)[76] of electronic products led to an increase in emissions of 153 percent between 1990 and 1999, when

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[75] The GWP of PFPMIE, a perfluoropolyether used as an F-HTF, is included in the *IPCC Fourth Assessment Report* with a value of 10,300. The GWPs of the perfluorinated amines and perfluoroalkylmorpholines that are used as F-HTFs have not been evaluated in the peer-reviewed literature. However, evaluations by the manufacturer indicate that their GWPs are near 10,000 (78 FR 20632), which is expected given that these compounds are both saturated and fully fluorinated. EPA assigns a default GWP of 10,000 to compounds that are both saturated and fully fluorinated and that do not have chemical-specific GWPs in either the Fourth or the Fifth Assessment Reports.

[76] Complexity is a term denoting the circuit required to connect the active circuit elements (transistors) on a chip. Increasing miniaturization, for the same chip size, leads to increasing transistor density, which, in turn, requires more complex interconnections between those transistors. This increasing complexity is manifested by increasing the levels (i.e., layers) of wiring, with each wiring layer requiring fluorinated gas usage for its manufacture.

emissions peaked at 9.1 MMT CO_2 Eq. Emissions began to decline after 1999, reaching a low point in 2009 before rebounding to 2006 emission levels and more or less plateauing at the current level, which represents a 48 percent decline from 1999 to 2020. Together, industrial growth, adoption of emissions reduction technologies (including but not limited to abatement technologies) and shifts in gas usages resulted in a net increase in emissions of approximately 32 percent between 1990 and 2020. Total emissions from semiconductor manufacture in 2020 were slightly higher than 2019 emissions, increasing by less than 1 percent, largely due to a large increase in N_2O emissions.

For 2020, total GWP-weighted emissions of all fluorinated greenhouse gases and N_2O from deposition, etching, and chamber cleaning processes in the U.S. semiconductor industry were estimated to be 4.7 MMT CO_2 Eq. This is a decrease in emissions from 1999 of 49 percent, and an increase in emissions from 1990 of 30 percent. These trends are driven by the above stated reasons.

Emissions from all fluorinated greenhouse gases from photovoltaic cells and MEMS manufacturing, are in Table 4-96. While EPA has developed a simple methodology to estimate emissions from non-reporters and to back-cast emissions from these sources for the entire time series, there is very high uncertainty associated with these emission estimates.

The emissions reported by facilities manufacturing MEMS included emissions of C_2F_6, C_3F_8, c-C_4F_8, CF_4, HFC-23, NF_3, N_2O and SF_6,[77] and were equivalent to only 0.096 percent to 0.233 percent of the total reported emissions from electronics manufacturing in 2011 to 2020. F-GHG emissions, the primary type of emissions for MEMS, ranged from 0.0003 to 0.0107 MMT CO_2 Eq. from 1991 to 2020. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing (GHGRP reporters must choose a single classification per fab). Emissions from non-reporters have not been estimated.

Total GWP-weighted emissions from manufacturing of photovoltaic cells were estimated to range from 0.0003 MMT CO_2 Eq. to 0.0235 MMT CO_2 Eq. from 1998 to 2020 and were equivalent to between 0.003 percent to 0.496 percent of the total reported emissions from electronics manufacturing. F-GHG emissions, the primary type of emissions for photovoltaic cells, ranged from 0.0003 to 0.0222 MMT CO_2 Eq. from 1998 to 2020. Emissions from manufacturing of photovoltaic cells were estimated using an emission factor developed from reported data from a single manufacturer between 2015 and 2016. This emission factor was then applied to production capacity estimates from non-reporting facilities. Reported emissions from photovoltaic cell manufacturing consisted of CF_4, C_2F_6, c-C_4F_8, CHF_3, NF_3, and N_2O.[78]

Emissions of F-HTFs, grouped by HFCs, PFCs or SF_6 are presented in Table 4-96. Table 4-98 shows F-HTF emissions in tons by compound group based on reporting to EPA's Greenhouse Gas Reporting Program (GHGRP) by semiconductor manufacturers during years 2014 through 2020. Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only.

Since reporting of F-HTF emissions began under EPA's GHGRP in 2011, total F-HTF emissions (reported and estimated non-reported) have fluctuated between 0.6 MMT CO_2 Eq. and 0.9 MMT CO_2 Eq., with an overall declining trend. An analysis of the data reported to EPA's GHGRP indicates that F-HTF emissions account for anywhere between 13 percent and 19 percent of total annual emissions (F-GHG, N_2O and F-HTFs) from

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[77] Gases not reported by MEMS manufacturers to the GHGRP are currently listed as "NE" in the CRF. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

[78] Gases not reported by PV manufacturers to the GHGRP are currently listed as "NE" in the CRF. Since no facilities report using these gases, emissions of these gases are not estimated for this sub-sector. However, there is insufficient data to definitively conclude that they are not used by non-reporting facilities.

semiconductor manufacturing.[79] Table 4-98 shows F-HTF emissions in tons by compound group based on reporting to EPA's GHGRP during years 2014 through 2020.[80]

Table 4-96: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Electronics Industry (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
CF_4	0.8	1.1	1.5	1.6	1.7	1.6	1.7
C_2F_6	2.0	2.0	1.2	1.2	1.1	1.0	0.9
C_3F_8	+	0.1	0.1	0.1	0.1	0.1	0.1
C_4F_8	0.0	0.1	0.1	0.1	0.1	0.1	0.1
HFC-23	0.2	0.2	0.3	0.4	0.4	0.4	0.4
SF_6	0.5	0.7	0.8	0.7	0.8	0.7	0.7
NF_3	+	0.5	0.6	0.6	0.6	0.6	0.6
C_4F_6	+	+	+	+	+	+	+
C_5F_8	+	+	+	+	+	+	+
CH_2F_2	+	+	+	+	+	+	+
CH_3F	+	+	+	+	+	+	+
CH_2FCF_3	+	+	+	+	+	+	+
Total Semiconductors	**3.6**	**4.6**	**4.7**	**4.6**	**4.8**	**4.4**	**4.4**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_3F_8	0.0	+	0.0	0.0	0.0	0.0	0.0
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	+	+	+	+	+	+
NF_3	0.0	+	+	+	+	+	+
Total MEMS	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
CF_4	0.0	+	+	+	+	+	+
C_2F_6	0.0	+	+	+	+	+	+
C_4F_8	0.0	+	+	+	+	+	+
HFC-23	0.0	+	+	+	+	+	+
SF_6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total PV	**0.0**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (Semiconductors)	+	0.1	0.2	0.3	0.3	0.2	0.3
N_2O (MEMS)	0.0	+	+	+	+	+	+
N_2O (PV)	0.0	+	+	+	+	+	+
Total N_2O	**+**	**0.1**	**0.2**	**0.3**	**0.3**	**0.2**	**0.3**
HFC, PFC and SF_6 F-HTFs	0.0	+	+	+	+	+	+
Total Electronics Industry	**3.6**	**4.8**	**5.0**	**4.9**	**5.1**	**4.7**	**4.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

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[79] Emissions data for HTFs (in tons of gas) from the semiconductor industry from 2011 through 2020 were obtained from the EPA GHGRP annual facility emissions reports.

[80] Many fluorinated heat transfer fluids consist of perfluoropolymethylisopropyl ethers (PFPMIEs) of different molecular weights and boiling points that are distilled from a mixture. "BP 200 °C" (and similar terms below) indicate the boiling point of the fluid in degrees Celsius. For more information, see https://www.regulations.gov/document?D=EPA-HQ-OAR-2009-0927-0276.

Table 4-97: PFC, HFC, SF_6, NF_3, and N_2O Emissions from Semiconductor Manufacture (Metric Tons)

Year	1990	2005	2016	2017	2018	2019	2020
CF_4	114.8	146.2	208.6	219.8	234.7	219.0	224.5
C_2F_6	160.0	161.7	99.5	97.6	92.9	79.1	70.3
C_3F_8	0.4	9.0	14.3	11.7	12.1	10.1	9.0
C_4F_8	0.0	11.4	5.4	5.8	6.0	5.7	5.7
HFC-23	14.6	13.7	23.2	25.7	26.5	25.5	26.5
SF_6	21.7	30.7	35.7	30.0	33.4	32.4	31.8
NF_3	2.8	28.5	33.2	32.8	34.1	33.2	36.1
C_4F_6	0.7	0.9	1.0	0.9	0.8	0.9	0.8
C_5F_8	0.4	0.6	0.5	0.8	0.5	1.2	0.4
CH_2F_2	0.7	0.9	0.9	1.1	0.9	1.0	1.1
CH_3F	1.5	2.0	1.9	2.3	3.0	2.5	2.8
CH_2FCF_3	+	+	+	+	+	+	+
N_2O	120.2	412.0	789.8	911.3	852.0	781.6	993.1

+ Does not exceed 0.05 MT.

Table 4-98: F-HTF Emissions from Electronics Manufacture by Compound Group (kt CO_2 Eq.)

Year	2014	2015	2016	2017	2018	2019	2020
HFCs	3.3	3.0	4.1	3.6	2.7	1.1	0.9
PFCs	1.6	2.8	2.6	9.1	10.0	8.4	1.8
SF_6	20.7	12.8	11.4	16.6	13.2	6.0	12.8
HFEs	4.8	4.2	7.5	2.9	4.6	1.3	5.3
PFPMIEs	182.2	208.1	173.7	148.5	183.0	171.7	149.9
Perfluoalkylromorpholines	108.3	81.5	75.7	52.3	58.6	56.4	60.9
Perfluorotrialkylamines	490.4	438.9	386.7	383.9	410.7	363.6	379.8
Total F-HTFs	**811.4**	**751.4**	**661.7**	**616.9**	**682.9**	**608.4**	**611.3**

Note: Emissions of F-HTFs that are not HFCs, PFCs or SF_6 are not included in inventory totals and are included for informational purposes only. Emissions presented for informational purposes include HFEs, PFPMIEs, perfluoroalkylmorpholines, and perfluorotrialkylamines.

Methodology and Time-Series Consistency

Emissions are based on data reported through Subpart I, Electronics Manufacture, of EPA's GHGRP, semiconductor manufacturing Partner-reported emissions data received through EPA's PFC[81] Reduction/Climate Partnership, EPA's PFC Emissions Vintage Model (PEVM)—a model that estimates industry emissions from etching and chamber cleaning processes in the absence of emission control strategies (Burton and Beizaie 2001)[82]—and estimates of industry activity (i.e., total manufactured layer area and manufacturing capacity). The availability and applicability of reported emissions data from the EPA Partnership and EPA's GHGRP and activity data differ across the 1990 through 2020 time series. Consequently, fluorinated greenhouse gas (F-GHG) emissions from etching and chamber cleaning processes for semiconductors were estimated using seven distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, 2000 through 2006, 2007 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2020. Nitrous oxide emissions were estimated using five distinct methods, one each for the period 1990 through 1994, 1995 through 2010, 2011 and 2012, 2013 and 2014, and 2015 through 2020. The

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[81] In the context of the EPA Partnership and PEVM, PFC refers to perfluorocompounds, not perfluorocarbons.

[82] A Partner refers to a participant in the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily reported their PFC emissions to the EPA by way of a third party, which aggregated the emissions through 2010.

methodology discussion below for these time periods focuses on semiconductor emissions from etching, chamber cleaning, and uses of N_2O. Other emissions for MEMS, photovoltaic cells, and HTFs were estimated using the approaches described immediately below.

MEMS

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of MEMS are available for the years 2011 to 2020. Emissions from manufacturing of MEMS for years prior to 2011 were calculated by linearly interpolating emissions between 1990 (at zero MMT CO_2 Eq.) and 2011, the first year where emissions from manufacturing of MEMS was reported to the GHGRP. Based upon information in the World Fab Forecast (WFF), it appears that some GHGRP reporters that manufacture both semiconductors and MEMS are reporting their emissions as only from semiconductor manufacturing; however, emissions from MEMS manufacturing are likely being included in semiconductor totals. Emissions were not estimated for non-reporters.

Photovoltaic Cells

GHGRP-reported emissions (F-GHG and N_2O) from the manufacturing of photovoltaic cells are available for 2011, 2012, 2015, and 2016 from two manufacturers. EPA estimates the emissions from manufacturing of PVs from non-reporting facilities by multiplying the estimated capacity of non-reporters by a calculated F-GHG emission factor and N_2O emission factor based on GHGRP reported emissions from the manufacturer (in MMT CO_2 Eq. per megawatt) that reported emissions in 2015 and 2016. This manufacture's emissions are expected to be more representative of emissions from the sector, as their emissions were consistent with consuming only CF_4 for etching processes and are a large-scale manufacturer, representing 28 percent of the U.S. production capacity in 2016. The second photovoltaic manufacturer only produced a small fraction of U.S. production (<3 percent). They also reported the use of NF_3 in remote plasma cleaning processes, which does not have an emission factor in Part 98 for PV manufacturing, requiring them to report emissions equal to consumption. The total F-GHG emissions from non-reporters are then disaggregated into individual gases using the gas distribution from the 2015 to 2016 manufacturer. Manufacturing capacities in megawatts were drawn from DisplaySearch, a 2015 Congressional Research Service Report on U.S. Solar Photovoltaic Manufacturing, and self-reported capacity by GHGRP reporters. EPA estimated that during the 2015 to 2016 period, 28 percent of manufacturing capacity in the United States was represented through reported GHGRP emissions. Capacities are estimated for the full time series by linearly scaling the total U.S. capacity between zero in 1997 to the total capacity reported of crystalline silicon (c-Si) PV manufacturing in 2000 in DisplaySearch and then linearly scaling between the total capacity of c-Si PV manufacturing in DisplaySearch in 2009 to the total capacity of c-Si PV manufacturing reported in the Congressional Research Service report in 2012. Capacities were held constant for non-reporters for 2012 to 2020. Average emissions per MW from the GHGRP reporter in 2015 and 2016 were then applied to the total capacity prior to 2015. Emissions for 2014 from the GHGRP reporter that reported in 2015 and 2016 were scaled to the number of months open in 2014. For 1998 through 2020, emissions per MW (capacity) from the GHGRP reporter were applied to the non-reporters. For 2017 through 2020, there are no reported PV emissions. Therefore, emissions were estimated using the EPA-derived emission factor and estimated manufacturing capacity from non-reporters only.

HTFs

Facility emissions of F-HTFs from semiconductor manufacturing are reported to EPA under its GHGRP and are available for the years 2011 through 2020. EPA estimates the emissions of F-HTFs from non-reporting semiconductor facilities by calculating the ratio of GHGRP-reported fluorinated HTF emissions to GHGRP reported F-GHG emissions from etching and chamber cleaning processes, and then multiplying this ratio by the F-GHG emissions from etching and chamber cleaning processes estimated for non-reporting facilities. Fluorinated HTF use in semiconductor manufacturing is assumed to have begun in the early 2000s and to have gradually displaced other HTFs (e.g., de-ionized water and glycol) in semiconductor manufacturing (EPA 2006). For time-series consistency, EPA interpolated the share of F-HTF emissions to F-GHG emissions between 2000 (at 0 percent) and

2011 (at 22 percent) and applied these shares to the unadjusted F-GHG emissions during those years to estimate the fluorinated HTF emissions.

Semiconductors

1990 through 1994

From 1990 through 1994, Partnership data were unavailable, and emissions were modeled using PEVM (Burton and Beizaie 2001).[83] The 1990 to 1994 emissions are assumed to be uncontrolled, since reduction strategies such as chemical substitution and abatement were yet to be developed.

PEVM is based on the recognition that fluorinated greenhouse gas emissions from semiconductor manufacturing vary with: (1) the number of layers that comprise different kinds of semiconductor devices, including both silicon wafer and metal interconnect layers, and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of manufactured layer-area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest manufactured feature size),[84] and (2) product type (discrete, memory or logic).[85] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per Integrated Circuit (IC) specific to product type (Burton and Beizaie 2001; ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth technology from published data on annual wafer starts and average wafer size (VLSI Research, Inc. 2012).

The emission factor in PEVM is the average of four historical emission factors, each derived by dividing the total annual emissions reported by the Partners for each of the four years between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Over this period, the emission factors varied relatively little (i.e., the relative standard deviation for the average was 5 percent). Since Partners are believed not to have applied significant emission reduction measures before 2000, the resulting average emission factor reflects uncontrolled emissions and hence may be use here to estimate 1990 through 1994 emissions. The emission factor is used to estimate U.S. uncontrolled emissions using publicly available data on world (including U.S.) silicon consumption.

As it was assumed for this time period that there was no consequential adoption of fluorinated-gas-reducing measures, a fixed distribution of fluorinated-gas use was assumed to apply to the entire U.S. industry to estimate gas-specific emissions. This distribution was based upon the average fluorinated-gas purchases made by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001).

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[83] Various versions of the PEVM exist to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emissions factors, which were derived from Partner reported data for those years.

[84] By decreasing features of Integrated Circuit components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with 65 nm feature sizes might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality, while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS 2007).

[85] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

PEVM only addressed the seven main F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, HFC-23, SF_6, and NF_3) used in semiconductor manufacturing. Through reporting under Subpart I of EPA's GHGRP, data on other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) used in semiconductor manufacturing became available and EPA was therefore able to extrapolate this data across the entire 1990 to 2020 timeseries. To estimate emissions for these "other F-GHGs", emissions data from Subpart I were used to estimate the average share or percentage contribution of these gases as compared to total F-GHG emissions and then these shares were applied to all years prior to reported data from Subpart I (1990 through 2010) and to the emissions from non-reporters from 2011 to 2020.

To estimate N_2O emissions, it was assumed the proportion of N_2O emissions estimated for 1995 (discussed below) remained constant for the period of 1990 through 1994.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more representative (e.g., in terms of capacity utilization in a given year) than PEVM-estimated emissions and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total capacity of the plants operated by the Partners and the total capacity of all of the semiconductor plants in the United States; this ratio represents the share of capacity attributable to the Partnership. This method assumes that Partners and non-Partners have identical capacity utilizations and distributions of manufacturing technologies. Plant capacity data is contained in the World Fab Forecast (WFF) database and its predecessors, which is updated quarterly. Gas-specific emissions were estimated using the same method as for 1990 through 1994.

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

For this time period, the N_2O emissions were estimated using an emission factor that was applied to the annual, total U.S. TMLA manufactured. The emission factor was developed using a regression-through-the-origin (RTO) model: GHGRP reported N_2O emissions were regressed against the corresponding TMLA of facilities that reported no use of abatement systems. Details on EPA's GHGRP reported emissions and development of emission factor using the RTO model are presented in the 2011 through 2012 section. The total U.S. TMLA for 1995 through 1999 was estimated using PEVM.

2000 through 2006

Emissions for the years 2000 through 2006—the period during which Partners began the consequential application of fluorinated greenhouse gas-reduction measures—were estimated using a combination of Partner-reported emissions and adjusted PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions, those from non-Partners, were estimated using PEVM, with one change. To ensure time-series consistency and to reflect the increasing use of remote clean technology (which increases the efficiency of the production process while lowering emissions of fluorinated greenhouse gases), the average non-Partner emission factor (PEVM emission factor) was assumed to begin declining gradually during this period. Specifically, the non-Partner emission factor for each year was determined by linear interpolation, using the end points of 1999 (the original PEVM emission factor) and 2011 (a new emission factor determined for the non-Partner population based on GHGRP-reported data, described below).

The portion of the U.S. total emissions attributed to non-Partners is obtained by multiplying PEVM's total U.S. emissions figure by the non-Partner share of U.S. total silicon capacity for each year as described above.[86] Gas-specific emissions from non-Partners were estimated using linear interpolation between the gas-specific emissions distributions of 1999 (assumed to be the same as that of the total U.S. Industry in 1994) and 2011 (calculated from

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[86] This approach assumes that the distribution of linewidth technologies is the same between Partners and non-Partners. As discussed in the description of the method used to estimate 2007 emissions, this is not always the case.

a subset of non-Partners that reported through the GHGRP as a result of emitting more than 25,000 MT CO_2 Eq. per year). Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see ITRS 2008 and Semiconductor Equipment and Materials Industry 2011).[87, 88, 89]

For this time period emissions of other F-GHGs (C_4F_6, C_5F_8, HFC-32, HFC-41, HFC-134a) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2007 through 2010

For the years 2007 through 2010, emissions were also estimated using a combination of Partner reported emissions and adjusted PEVM modeled emissions to provide estimates for non-Partners; however, two improvements were made to the estimation method employed for the previous years in the time series. First, the 2007 through 2010 emission estimates account for the fact that Partners and non-Partners employ different distributions of manufacturing technologies, with the Partners using manufacturing technologies with greater transistor densities and therefore greater numbers of layers.[90] Second, the scope of the 2007 through 2010 estimates was expanded relative to the estimates for the years 2000 through 2006 to include emissions from research and development (R&D) fabs. This additional enhancement was feasible through the use of more detailed data published in the WFF. PEVM databases were updated annually as described above. The published world average capacity utilization for 2007 through 2010 was used for production fabs, while for R&D fabs a 20 percent figure was assumed (SIA 2009).

In addition, publicly available utilization data was used to account for differences in fab utilization for manufacturers of discrete and IC products for 2010 emissions for non-Partners. The Semiconductor Capacity Utilization (SICAS) Reports from SIA provides the global semiconductor industry capacity and utilization, differentiated by discrete and IC products (SIA 2009 through 2011). PEVM estimates were adjusted using

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[87] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2 to 3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFF were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percent. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers, and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities were estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV) to determine the average design capacity over the 2006 period.

[88] In 2006, the industry trend in co-ownership of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases are not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. manufacturing capacity.

[89] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time, discrete devices did not use PFCs during manufacturing and therefore only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards, discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

[90] EPA considered applying this change to years before 2007, but found that it would be difficult due to the large amount of data (i.e., technology-specific global and non-Partner TMLA) that would have to be examined and manipulated for each year. This effort did not appear to be justified given the relatively small impact of the improvement on the total estimate for 2007 and the fact that the impact of the improvement would likely be lower for earlier years because the estimated share of emissions accounted for by non-Partners is growing as Partners continue to implement emission-reduction efforts.

technology-weighted capacity shares that reflect the relative influence of different utilization. Gas-specific emissions for non-Partners were estimated using the same method as for 2000 through 2006.

For this time period emissions of other F-GHGs (C_5F_8, CH_2F_2, CH_3F, CH_2FCF_3, $C_2H_2F_4$) were estimated using the method described above for 1990 to 1994.

Nitrous oxide emissions were estimated using the same methodology as the 1995 through 1999 methodology.

2011 through 2012

The fifth method for estimating emissions from semiconductor manufacturing covers the period 2011 through 2012. This methodology differs from previous years because the EPA's Partnership with the semiconductor industry ended (in 2010) and reporting under EPA's GHGRP began. Manufacturers whose estimated uncontrolled emissions equal or exceed 25,000 MT CO_2 Eq. per year (based on default F-GHG-specific emission factors and total capacity in terms of substrate area) are required to report their emissions to EPA. This population of reporters to EPA's GHGRP included both historical Partners of EPA's PFC Reduction/Climate Partnership as well as non-Partners some of which use gallium arsenide (GaAs) technology in addition to Si technology.[91] Emissions from the population of manufacturers that were below the reporting threshold were also estimated for this time period using EPA-developed emission factors and estimates of facility-specific production obtained from WFF. Inventory totals reflect the emissions from both reporting and non-reporting populations.

Under EPA's GHGRP, semiconductor manufacturing facilities report emissions of F-GHGs (for all types of F-GHGs) used in etch and clean processes as well as emissions of fluorinated heat transfer fluids. (Fluorinated heat transfer fluids are used to control process temperatures, thermally test devices, and clean substrate surfaces, among other applications.) They also report N_2O emissions from CVD and other processes. The F-GHGs and N_2O were aggregated, by gas, across all semiconductor manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. At this time, emissions that result from heat transfer fluid use that are HFC, PFC and SF_6 are included in the total emission estimates from semiconductor manufacturing, and these GHGRP-reported emissions have been compiled and presented in Table 4-96. F-HTF emissions resulting from other types of gases (e.g., HFEs) are not presented in semiconductor manufacturing totals in Table 4-96 and Table 4-97 but are shown in Table 4-98 for informational purposes.

Changes to the default emission factors and default destruction or removal efficiencies (DREs) used for GHGRP reporting affected the emissions trend between 2013 and 2014. These changes did not reflect actual emission rate changes but data improvements. Therefore, for the current Inventory, EPA adjusted the time series of GHGRP-reported data for 2011 through 2013 to ensure time-series consistency using a series of calculations that took into account the characteristics of a facility (e.g., wafer size and abatement use). To adjust emissions for facilities that did not report abatement in 2011 through 2013, EPA simply applied the revised emission factors to each facility's estimated gas consumption by gas, process type and wafer size. In 2014, EPA also started collecting information on fab-wide DREs and the gases abated by process type, which were used in calculations for adjusting emissions from facilities that abated F-GHGs in 2011 through 2013.

- To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first calculated the quantity of gas abated in 2014 using reported F-GHG emissions, the revised default DREs (or the estimated site-specific DRE,[92] if a site-specific DRE was indicated), and the fab-wide DREs reported in 2014.[93] To adjust emissions for facilities that abated emissions in 2011 through 2013, EPA first estimated

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[91] GaAs and Si technologies refer to the wafer on which devices are manufactured, which use the same PFCs but in different ways.

[92] EPA generally assumed site-specific DREs were as follows: CF_4, Etch (90 percent); all other gases, Etch (98 percent); NF_3, Clean (95 percent); CF_4, Clean (80 percent), and all other gases, Clean (80 percent). There were a few exceptions where a higher DRE was assumed to ensure the calculations operated correctly when there was 100 percent abatement.

[93] If abatement information was not available for 2014 or the reported incorrectly in 2014, data from 2015 or 2016 was substituted.

the percentage of gas passing through abatement systems for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 and NF_3.

- EPA then estimated the quantity of NF_3 abated for remote plasma clean in 2014 using the ratio of emissions reported for CF_4 (which is not abated) and NF_3. This abated quantity was then subtracted from the total abated quantity calculated as described in the bullet above.
- To account for the resulting remaining abated quantity, EPA assumed that the percentage of gas passing through abatement systems was the same across all remaining gas and process type combinations where abatement was reported for 2014.
- The percentage of gas abated was then assumed to be the same in 2011 through 2013 (if the facility claimed abatement that year) as in 2014 for each gas abated in 2014.

The revised emission factors and DREs were then applied to the estimated gas consumption for each facility by gas, process type and wafer size.[94]

For the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP, emission estimates are based on EPA-developed emission factors for the F-GHGs and N_2O and estimates of manufacturing activity. The new emission factors (in units of mass of CO_2 Eq./TMLA [million square inches (MSI)]) are based on the emissions reported under EPA's GHGRP by facilities without abatement and on the TMLA estimates for these facilities based on the WFF (SEMI 2012, 2013).[95] In a refinement of the method used to estimate emissions for the non-Partner population for prior years, different emission factors were developed for different subpopulations of fabs, disaggregated by wafer size (200 mm and 300 mm). For each of these groups, a subpopulation-specific emission factor was obtained using a regression-through-the-origin (RTO) model: facility-reported aggregate emissions of seven F-GHGs (CF_4, C_2F_6, C_3F_8, c-C_4F_8, CHF_3, SF_6 and NF_3)[96] were regressed against the corresponding TMLA to estimate an aggregate F-GHG emissions factor (CO_2 Eq./MSI TMLA), and facility-reported N_2O emissions were regressed against the corresponding TMLA to estimate a N_2O emissions factor (CO_2 Eq./MSI TMLA). For each subpopulation, the slope of the RTO model is the emission factor for that subpopulation. Information on the use of point-of-use abatement by non-reporting fabs was not available; thus, EPA conservatively assumed that non-reporting facilities did not use point-of-use abatement.

For 2011 and 2012, estimates of TMLA relied on the capacity utilization of the fabs published by the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012). Similar to the assumption for 2007 through 2010, facilities with only R&D activities were assumed to utilize only 20 percent of their manufacturing capacity. All other facilities in the United States are assumed to utilize the average percent of the manufacturing capacity without distinguishing whether fabs produce discrete products or logic products.

Non-reporting fabs were then broken out into subpopulations by wafer size (200 mm and 300 mm). using information available through the WFF. The appropriate emission factor was applied to the total TMLA of each subpopulation of non-reporting facilities to estimate the GWP-weighted emissions of that subpopulation.

Gas-specific, GWP-weighted emissions for each subpopulation of non-reporting facilities were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions from which the aggregate emission factors, based on GHGRP-reported data, were developed. Estimated in this manner, the non-reporting population

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[94] Since facilities did not report by fab before 2014, fab-wide DREs were averaged if a facility had more than one fab. For facilities that reported more than one wafer size per facility, the percentages of a facility's emissions per wafer size were estimated in 2014 and applied to earlier years, if possible. If the percentage of emissions per wafer size were unknown, a 50/50 split was used.

[95] EPA does not have information on fab-wide DREs for this time period, so it is not possible to estimate uncontrolled emissions from fabs that reported point-of-use abatement. These fabs were therefore excluded from the regression analysis. (They are still included in the national totals.)

[96] Only seven gases were aggregated because inclusion of F-GHGs that are not reported in the Inventory results in overestimation of emission factor that is applied to the various non-reporting subpopulations.

accounted for 4.9 and 5.0 percent of U.S. emissions in 2011 and 2012, respectively. The GHGRP-reported emissions and the calculated non-reporting population emissions are summed to estimate the total emissions from semiconductor manufacturing.

2013 and 2014

For 2013 and 2014, as for 2011 and 2012, F-GHG and N_2O emissions data received through EPA's GHGRP were aggregated, by gas, across all semiconductor-manufacturing GHGRP reporters to calculate gas-specific emissions for the GHGRP-reporting segment of the U.S. industry. However, for these years WFF data was not available. Therefore, an updated methodology that does not depend on the WFF derived activity data was used to estimate emissions for the segment of the industry that are not covered by EPA's GHGRP. For the facilities that did not report to the GHGRP (i.e., which are below EPA's GHGRP reporting threshold or are R&D facilities), emissions were estimated based on the proportion of total U.S. emissions attributed to non-reporters for 2011 and 2012. EPA used a simple averaging method by first estimating this proportion for both F-GHGs and N_2O for 2011, 2012, and 2015 through 2020, resulting in one set of proportions for F-GHGs and one set for N_2O, and then applied the average of each set to the 2013 and 2014 GHGRP reported emissions to estimate the non-reporters' emissions. Fluorinated gas-specific, GWP-weighted emissions for non-reporters were estimated using the corresponding reported distribution of gas-specific, GWP-weighted emissions reported through EPA's GHGRP for 2013 and 2014.

GHGRP-reported emissions in 2013 were adjusted to capture changes to the default emission factors and default destruction or removal efficiencies used for GHGRP reporting, affecting the emissions trend between 2013 and 2014. EPA used the same method to make these adjustments as described above for 2011 and 2012 GHGRP data.

2015 through 2020

Similar to the methods described above for 2011 and 2012, and 2013 and 2014, EPA relied upon emissions data reported directly through the GHGRP. For 2015 through 2020, EPA took an approach similar to the one used for 2011 and 2012 to estimate emissions for the segment of the semiconductor industry that is below EPA's GHGRP reporting threshold, and for R&D facilities, which are not covered by EPA's GHGRP. However, in a change from previous years, EPA was able to develop new annual emission factors for 2015 through 2020 using TMLA from WFF and a more comprehensive set of emissions, i.e., fabs with as well as without abatement control, as new information about the use of abatement in GHGRP fabs and fab-wide were available. Fab-wide DREs represent total fab CO_2 Eq.-weighted controlled F-GHG and N_2O emissions (emissions after the use of abatement) divided by total fab CO_2 Eq.-weighted uncontrolled F-GHG and N_2O emissions (emission prior to the use of abatement).

Using information about reported emissions and the use of abatement and fab-wide DREs, EPA was able to calculate uncontrolled emissions (each total F-GHG and N_2O) for every GHGRP reporting fab. Using this, coupled with TMLA estimated using methods described above (see 2011 through 2012), EPA derived emission factors by year, gas type (F-GHG or N_2O), and wafer size (200 mm and less or 300 mm) by dividing the total annual emissions reported by GHGRP reporters by the total TMLA estimated for those reporters. These emission factors were multiplied by estimates of non-reporter TMLA to arrive at estimates of total F-GHG and N_2O emissions for non-reporters for each year. For each wafer size, the total F-GHG emissions were disaggregated into individual gases using the shares of total emissions represented by those gases in the emissions reported to the GHGRP by unabated fabs producing that wafer size.

Data Sources

GHGRP reporters, which consist of former EPA Partners and non-Partners, estimated their emissions using a default emission factor method established by EPA. Like the Tier 2c Method in the *2019 Refinement to the 2006 IPCC Guidelines*, this method uses different emission and byproduct generation factors for different F-GHGs and process types and uses factors for different wafer sizes (i.e., 300mm vs. 150 and 200mm) and CVD clean subtypes (in situ thermal, in situ plasma, and remote plasma). Starting with 2014 reported emissions, EPA's GHGRP required semiconductor manufacturers to apply updated emission factors to estimate their F-GHG emissions. For the years 2011 through 2013 reported emissions, semiconductor manufacturers used older emission factors to estimate their F-GHG emissions (Federal Register / Vol. 75, No. 230 /December 1, 2010, 74829). Subpart I emission factors were updated for 2014 by EPA as a result of a larger set of emission factor data becoming available as part of the Subpart I petition process, which took place from 2011 through 2013. In addition to semiconductor manufacturing, GHGRP also includes reported emissions from MEMS and PV producers.

Historically, semiconductor industry partners estimated and reported their emissions using a range of methods and uneven documentation. It is assumed that most Partners used a method at least as accurate as the IPCC's Tier 2a Methodology, recommended in the *2006 IPCC Guidelines*. Partners are estimated to have accounted for between 56 and 79 percent of F-GHG emissions from U.S. semiconductor manufacturing between 1995 and 2010, with the percentage declining in recent years as Partners increasingly implemented abatement measures.

Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) WFF (formerly World Fab Watch) database (1996 through 2012, 2013, 2016, 2018, and 2021) (e.g., Semiconductor Materials and Equipment Industry 2021). Actual worldwide capacity utilizations for 2008 through 2010 were obtained from Semiconductor International Capacity Statistics (SICAS) (SIA 2009 through 2011). Estimates of the number of layers for each linewidth was obtained from International Technology Roadmap for Semiconductors: 2013 Edition (Burton and Beizaie 2001; ITRS 2007; ITRS 2008; ITRS 2011; ITRS 2013). PEVM utilized the WFF, SICAS, and ITRS, as well as historical silicon consumption estimates published by VLSI. Actual quarterly U.S. capacity utilizations for 2011, 2012, 2015 and 2016 were obtained from the U.S. Census Bureau's Historical Data Quarterly Survey of Plant Capacity Utilization (USCB 2011, 2012, 2015, and 2016).

Estimates of PV manufacturing capacity, which are used to calculate emissions from non-reporting facilities, are based on data from two sources. A historical market analysis from DisplaySearch provided estimates of U.S. manufacturing capacity from 2000-2009 (DisplaySearch 2010). Domestic PV cell production for 2012 was obtained from a Congressional Research Service report titled *U.S. Solar Photovoltaic Manufacturing: Industry Trends, Global Competition, Federal Support* (Platzer 2015).

Uncertainty

A quantitative uncertainty analysis of this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The Monte Carlo Stochastic Simulation was performed on the total emissions estimate from the Electronics Industry, represented in equation form as:

Equation 4-19: Total Emissions from Electronics Industry

$$\text{Total Emissions } (E_{T}) = \text{Semiconductors F-GHG and } N_2O \text{ Emissions } (E_{Semi}) + \text{MEMS F-GHG and } N_2O \text{ Emissions } (E_{MEMS}) + \text{PV F-GHG and } N_2O \text{ Emissions } (E_{PV}) + \text{HFC, PFC and } SF_6 \text{ F-HTFs Emissions } (E_{HTF})$$

The uncertainty in the total emissions for the Electronics Industry, presented in Table 4-99 below, results from the convolution of four distributions of emissions, namely from semiconductors manufacturing, MEMS manufacturing, PV Manufacturing and emissions of Heat Transfer Fluids. The approaches for estimating uncertainty in each of the sources are described below:

Semiconductors Manufacture Emission Uncertainty

The Monte Carlo Stochastic Simulation was performed on the emissions estimate from semiconductor manufacturing, represented in equation form as:

Equation 4-20: Total Emissions from Semiconductor Manufacturing

$$\text{Semiconductors F-GHG and } N_2O \text{ Emissions } (E_{Semi}) = \text{GHGRP Reported F-GHG Emissions } (E_{R,\text{F-GHG, Semi}}) + \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,\text{F-GHG,Semi}}) + \text{GHGRP Reported } N_2O \text{ Emissions } (E_{R,N_2O,Semi}) + \text{Non-Reporters' Estimated } N_2O \text{ Emissions } (E_{NR,N_2O,Semi})$$

The uncertainty in E_{Semi} results from the convolution of four distributions of emissions, $E_{R,F\text{-}GHG,Semi}$ $E_{R,N2O,Semi}$ $E_{NR,F\text{-}GHG,Semi}$ and $E_{NR,N2O,Semi}$. The approaches for estimating each distribution and combining them to arrive at the reported 95 percent confidence interval (CI) for E_{Semi} are described in the remainder of this section.

The uncertainty estimate of $E_{R,\ F\text{-}GHG,Semi}$, or GHGRP-reported F-GHG emissions, is developed based on gas-specific uncertainty estimates of emissions for two industry segments, one processing 200 mm or less wafers and one processing 300 mm wafers. Uncertainties in emissions for each gas and industry segment are based on an uncertainty analysis conducted during the assessment of emission estimation methods for the Subpart I rulemaking in 2012 (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028).[97] This assessment relied on facility-specific gas information by gas and wafer size, and incorporated uncertainty associated with both emission factors and gas consumption quantities. The 2012 analysis did not consider the use of abatement.

For the industry segment that manufactured 200 mm wafers, estimates of uncertainty at a 95 percent CI ranged from ±29 percent for C_3F_8 to ±10 percent for CF_4. For the corresponding 300 mm industry segment, estimates of uncertainty at the 95 percent CI ranged from ±36 percent for C_4F_8 to ±16 percent for CF_4. For gases for which uncertainty was not analyzed in the 2012 assessment (e.g., CH_2F_2), EPA applied the 95 percent CI range equivalent to the range for the gas and industry segment with the highest uncertainty from the 2012 assessment. These gas and wafer-specific uncertainty estimates were developed to represent uncertainty at a facility-level, but they are applied to the total emissions across all the facilities that did not abate emissions as reported under EPA's GHGRP at a national-level. Hence, it is noted that the uncertainty estimates used may be overestimating the uncertainties at a national-level.

For those facilities reporting abatement of emissions under EPA's GHGRP, estimates of uncertainties for the no abatement industry segments are modified to reflect the use of full abatement (abatement of all gases from all cleaning and etching equipment) and partial abatement. These assumptions used to develop uncertainties for the partial and full abatement facilities are identical for 200 mm and 300 mm wafer processing facilities. For all facilities reporting gas abatement, a triangular distribution of destruction or removal efficiency is assumed for each gas. The triangular distributions range from an asymmetric and highly uncertain distribution of zero percent minimum to 90 percent maximum with 70 percent most likely value for CF_4 to a symmetric and less uncertain distribution of 85 percent minimum to 95 percent maximum with 90 percent most likely value for C_4F_8, NF_3, and SF_6. For facilities reporting partial abatement, the distribution of fraction of the gas fed through the abatement device, for each gas, is assumed to be triangularly distributed as well. It is assumed that no more than 50 percent of the gases are abated (i.e., the maximum value) and that 50 percent is the most likely value, and the minimum is zero percent. Consideration of abatement then resulted in four additional industry segments, two 200-mm wafer-processing segments (one fully and one partially abating each gas) and two 300-mm wafer-processing segment (one fully and the other partially abating each gas). Gas-specific emission uncertainties were estimated by

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[97] On November 13, 2013, EPA published a final rule revising Subpart I (Electronics Manufacturing) of the GHGRP (78 FR 68162). The revised rule includes updated default emission factors and updated default destruction and removal efficiencies that are slightly different from those that semiconductor manufacturers were required to use to report their 2012 emissions. The uncertainty analyses that were performed during the development of the revised rule focused on these updated defaults but are expected to be reasonably representative of the uncertainties associated with the older defaults, particularly for estimates at the country level. (They may somewhat underestimate the uncertainties associated with the older defaults at the facility level.) For simplicity, the 2012 estimates are assumed to be unbiased although in some cases, the updated (and therefore more representative) defaults are higher or lower than the older defaults. Multiple models and sensitivity scenarios were run for the Subpart I analysis. The uncertainty analysis presented here made use of the Input gas and wafer size model (Model 1) under the following conditions: Year = 2010, f = 20, n = SIA3.

convolving the distributions of unabated emissions with the appropriate distribution of abatement efficiency for fully and partially abated facilities using a Monte Carlo simulation.

The uncertainty in $E_{R,F\text{-}GHG,Semi}$ is obtained by allocating the estimates of uncertainties to the total GHGRP-reported emissions from each of the six industry segments, and then running a Monte Carlo simulation which results in the 95 percent CI for emissions from GHGRP-reporting facilities ($E_{R,F\text{-}GHG,Semi}$).

The uncertainty in $E_{R,N2O,Semi}$ is obtained by assuming that the uncertainty in the emissions reported by each of the GHGRP reporting facilities results from the uncertainty in quantity of N_2O consumed and the N_2O emission factor (or utilization). Similar to analyses completed for Subpart I (see Technical Support for Modifications to the Fluorinated Greenhouse Gas Emission Estimation Method Option for Semiconductor Facilities under Subpart I, docket EPA–HQ–OAR–2011–0028), the uncertainty of N_2O consumed was assumed to be 20 percent. Consumption of N_2O for GHGRP reporting facilities was estimated by back-calculating from emissions reported and assuming no abatement. The quantity of N_2O utilized (the complement of the emission factor) was assumed to have a triangular distribution with a minimum value of zero percent, mode of 20 percent and maximum value of 84 percent. The minimum was selected based on physical limitations, the mode was set equivalent to the Subpart I default N_2O utilization rate for chemical vapor deposition, and the maximum was set equal to the maximum utilization rate found in ISMI Analysis of Nitrous Oxide Survey Data (ISMI 2009). The inputs were used to simulate emissions for each of the GHGRP reporting, N_2O-emitting facilities. The uncertainty for the total reported N_2O emissions was then estimated by combining the uncertainties of each facilities' reported emissions using Monte Carlo simulation.

The estimate of uncertainty in $E_{NR,\ F\text{-}GHG,Semi}$ and $E_{NR,\ N2O,Semi}$ entailed developing estimates of uncertainties for the emissions factors and the corresponding estimates of TMLA.

The uncertainty in TMLA depends on the uncertainty of two variables—an estimate of the uncertainty in the average annual capacity utilization for each level of production of fabs (e.g., full scale or R&D production) and a corresponding estimate of the uncertainty in the number of layers manufactured. For both variables, the distributions of capacity utilizations and number of manufactured layers are assumed triangular for all categories of non-reporting fabs. The most probable utilization is assumed to be 82 percent, with the highest and lowest utilization assumed to be 89 percent, and 70 percent, respectively. For the triangular distributions that govern the number of possible layers manufactured, it is assumed the most probable value is one layer less than reported in the ITRS; the smallest number varied by technology generation between one and two layers less than given in the ITRS and largest number of layers corresponded to the figure given in the ITRS.

The uncertainty bounds for the average capacity utilization and the number of layers manufactured are used as inputs in a separate Monte Carlo simulation to estimate the uncertainty around the TMLA of both individual facilities as well as the total non-reporting TMLA of each sub-population.

The uncertainty around the emission factors for non-reporting facilities is dependent on the uncertainty of the total emissions (MMT CO_2 Eq. units) and the TMLA of each reporting facility in that category. For each wafer size for reporting facilities, total emissions were regressed on TMLA (with an intercept forced to zero) for 10,000 emission and 10,000 TMLA values in a Monte Carlo simulation, which results in 10,000 total regression coefficients (emission factors). The 2.5th and the 97.5th percentile of these emission factors are determined, and the bounds are assigned as the percent difference from the estimated emission factor.

The next step in estimating the uncertainty in emissions of reporting and non-reporting facilities in semiconductor manufacture is convolving the distribution of reported emissions, emission factors, and TMLA using Monte Carlo simulation. For this Monte Carlo simulation, the distributions of the reported F-GHG gas- and wafer size-specific emissions are assumed to be normally distributed, and the uncertainty bounds are assigned at 1.96 standard deviations around the estimated mean. The were some instances, though, where departures from normality were observed for variables, including for the distributions of the gas- and wafer size-specific N_2O emissions, TMLA, and non-reporter emission factors, both for F-GHGs and N_2O. As a result, the distributions for these parameters were assumed to follow a pert beta distribution.

MEMS Manufacture Emission Uncertainty

The Monte Carlo Stochastic Simulation was performed on the emissions estimate from MEMS manufacturing, represented in equation form as:

Equation 4-21: Total Emissions from MEMS Manufacturing

$$\text{MEMS F-GHG and N}_2\text{O Emissions } (E_{MEMS}) = \text{GHGRP Reported F-GHG Emissions } (E_{R,F\text{-}GHG,MEMS}) + \text{GHGRP Reported N}_2\text{O Emissions } (E_{R,N_2O,\ MEMS})$$

Emissions from MEMS manufacturing are only quantified for GHGRP reporters. MEMS manufacturers that report to the GHGRP all report the use of 200 mm wafers. Some MEMS manufacturers report using abatement equipment. Therefore, the estimates of uncertainty at the 95 percent CI for each gas emitted by MEMS manufacturers are set equal to the gas-specific uncertainties for manufacture of 200mm semiconductor wafers with partial abatement. The same assumption is applied for uncertainty levels for GHGRP reported MEMS N_2O emissions ($E_{R,N2O,MEMS}$).

PV Manufacture Emission Uncertainty

The Monte Carlo Stochastic Simulation was performed on the emissions estimate from PV manufacturing, represented in equation form as:

Equation 4-22: Total Emissions from PV Manufacturing

$$\text{PV F-GHG and N}_2\text{O Emissions } (E_{PV}) = \text{Non-Reporters' Estimated F-GHG Emissions } (E_{NR,F\text{-}GHG,PV}) + \text{Non-Reporters' Estimated N}_2\text{O Emissions } (E_{NR,N_2O,PV})$$

Emissions from PV manufacturing are only estimated for non-GHGRP reporters. There were no reported emissions from PV manufacturing in GHGRP in 2020. The “Non-Reporters’ Estimated F-GHG Emissions” term was estimated using an emission factor developed using emissions from reported data in 2015 and 2016 and total non-reporters’ capacity. Due to a lack of information and data and because they represent similar physical and chemical processes, the uncertainty at the 95 percent I level for non-reporter PV capacity is assumed to be the same as the uncertainty in non-reporter TMLA for semiconductor manufacturing. Similarly, the uncertainty for the PV manufacture emission factors are assumed to be the same as the uncertainties in emission factors used for non-reporters in semiconductor manufacture.

Heat Transfer Fluids Emission Uncertainty

There is a lack of data related to the uncertainty of emission estimates of heat transfer fluids used for electronics manufacture. Therefore, per the *2006 IPCC Guidelines* (IPCC 2006, Volume 3, Chapter 6), uncertainty bounds of 20 percent were applied to the segments of PFCs, HFCs and SF6 at national levels.

The results of the Approach 2 quantitative uncertainty analysis for electronics manufacturing are summarized in Table 4-99. These results were obtained by convolving—using Monte Carlo simulation—the distributions of emissions for each reporting and non-reporting facility that manufactures semiconductors, MEMS, or PVs. The emissions estimate for total U.S. F-GHG, N_2O, and HTF emissions from electronics manufacturing were estimated to be between 4.45 and 5.03 MMT CO_2 Eq. at a 95 percent confidence level. This range represents 6 percent below to 6 percent above the 2020 emission estimate of 4.74 MMT CO_2 Eq. for all emissions from electronics manufacture. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate but were not explicitly modeled.

Table 4-99: Approach 2 Quantitative Uncertainty Estimates for HFC, PFC, SF_6, NF_3 and N_2O Emissions from Electronics Manufacture (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound[b]	Upper Bound[b]	Lower Bound	Upper Bound
Electronics Industry	HFC, PFC, SF_6, NF_3, and N_2O	4.74	4.45	5.03	-6%	6%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

QA/QC and Verification

For its GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[98] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

Emissions from 2015 through 2020 were updated to reflect updated emissions reporting in EPA's GHGRP, relative to the previous Inventory. Additionally, EPA made the following changes:

- To estimate non-reporter F-GHG and N_2O emissions, EPA relies on data reported through Subpart I and the World Fab Forecast. This process requires EPA to map facilities that report through Subpart I and which are also represented in the World Fab Forecast. For this inventory update, EPA identified and made corrections to a few instances of this mapping based on new information and additional reviews of the data. This had minimal effects on emission estimates.
- In the dataset used to estimate photovoltaics manufacturing capacity from 2000 to 2009, a correction was made to the formula which sums annual capacity across all producers. This resulted in slight changes to emissions estimates for the years where this dataset is used.
- Previously, all N_2O emissions were attributed solely to semiconductor manufacturing. For this inventory update, EPA revised the N_2O estimates by assigning emissions to the specific types of electronics manufacturing (i.e., semiconductor, photovoltaic cells, and MEMS). N_2O estimates are now reported with subtotals for each product type within the electronics industry.
- EPA revised the individual gases reported for semiconductor manufacturing to remove the "Other F-GHGs" category and replace it with separate totals for each individual gas. Similarly, EPA also updated the MEMS and photovoltaic cells estimates to show disaggregated totals for each individual HFC and PFC compound.
- A GHGRP fab that had previously been identified as a MEMS fab was determined to have produced photovoltaics. Their F-GHG emissions were removed from the MEMS totals and added to the PV totals.
- Previously, F-GHG emissions in 2016 from a PV manufacturer reporting through the GHGRP were held constant for 2017 through the most recent Inventory year. EPA determined that this manufacturer ceased operations in 2016, so their reported emissions were changed to zero for 2017 and beyond.

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[98] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

- To improve the uncertainty analysis for this source category other F-GHGs from semiconductor manufacturing, HFC, PFC, and SF_6 emissions from the use of heat transfer fluids and emissions resulting from the manufacturing of PVs and MEMS were included in total uncertainty estimates.

Overall, the impact of these recalculations led to an average decrease of 0.02 MMT CO_2 Eq. (0.44 percent) across the time series (1990 through 2019).

Planned Improvements

The Inventory methodology uses data reported through the EPA Partnership (for earlier years) and EPA's GHGRP (for later years) to extrapolate the emissions of the non-reporting population. While these techniques are well developed, the understanding of the relationship between the reporting and non-reporting populations is limited. Further analysis of the reporting and non-reporting populations could aid in the accuracy of the non-reporting population extrapolation in future years. In addition, the accuracy of the emissions estimates for the non-reporting population could be further increased through EPA's further investigation of and improvement upon the accuracy of estimated activity in the form of TMLA.

The Inventory uses utilization from two different sources for various time periods–SEMI to develop PEVM and to estimate non-Partner emissions for the period 1995 to 2010 and U.S. Census Bureau for 2011 through 2014. SEMI reported global capacity utilization for manufacturers through 2011. U.S. Census Bureau capacity utilization include U.S. semiconductor manufacturers as well as assemblers. Further analysis on the impacts of using a new and different source of utilization data could prove to be useful in better understanding of industry trends and impacts of utilization data sources on historical emission estimates.

Estimates of semiconductor non-reporter and non-Partner emissions are based on EPA-developed emission factors for the time periods pre-2010, 2011 through 2012, and 2015 through 2020. Based on the data available for these time periods, the methods used to develop emission factors for non-reporters and non-Partners are slightly inconsistent for semiconductors (e.g., how data representing emissions and TMLA from the manufacture of various wafer sizes are aggregated or disaggregated for purposes of calculating emission factors). Further analyses to support potentially adjusting the methods for developing these emission factors could be done to better ensure consistency across the time series.

The methodology for estimating semiconductor emissions from non-reporters uses data from the International Technology Roadmap for Semiconductors (ITRS) on the number of layers associated with various technology node sizes. The ITRS has now been replaced by the International Roadmap for Devices and Systems (IRDS), which has published updated data on the number of layers used in each device type and node size (in nanometers). Incorporating this updated dataset will improve the accuracy of emissions estimates from non-reporting semiconductor fabs.

4.24 Substitution of Ozone Depleting Substances (CRF Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone-depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[99] Ozone-depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone

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[99] [42 U.S.C § 7671, CAA Title VI].

layer, they are potent greenhouse gases. On December 27, 2020, the American Innovation and Manufacturing (AIM) Act was enacted by Congress and directs EPA to address HFCs by phasing down production and consumption (i.e., production plus import minus export), maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-100 and Table 4-101.[100]

Table 4-100: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
HFC-23	0.0	+	+	+	+	+	+
HFC-32	0.0	0.3	4.6	5.3	6.0	6.8	7.7
HFC-125	+	9.0	46.9	50.1	53.7	58.4	63.5
HFC-134a	+	80.1	69.1	64.7	62.1	60.9	59.5
HFC-143a	+	9.4	28.2	28.0	27.7	27.8	27.9
HFC-236fa	0.0	1.2	1.3	1.2	1.2	1.1	1.1
CF_4	0.0	+	+	+	0.1	0.1	0.1
Others[a]	0.2	7.2	14.9	16.1	16.6	16.8	16.6
Total	**0.2**	**107.2**	**165.1**	**165.5**	**167.3**	**171.8**	**176.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Others represent an unspecified mix of HFCs and PFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C_6F_{14}.

Note: Totals may not sum due to independent rounding.

Table 4-101: Emissions of HFCs and PFCs from ODS Substitution (Metric Tons)

Gas	1990	2005	2016	2017	2018	2019	2020
HFC-23	0	1	2	2	2	2	2
HFC-32	0	397	6,791	7,832	8,937	10,077	11,374
HFC-125	+	2,580	13,399	14,308	15,335	16,682	18,153
HFC-134a	+	56,029	48,337	45,264	43,419	42,558	41,590
HFC-143a	+	2,093	6,320	6,264	6,188	6,230	6,234
HFC-236fa	0	118	129	124	118	112	108
CF_4	0	2	6	6	7	7	7
Others[a]	M	M	M	M	M	M	M

+ Does not exceed 0.5 MT.

M (Mixture of Gases).

[a] Others represent an unspecified mix of HFCs and PFCs, which includes HFC-152a, HFC-227ea, HFC-245fa, HFC-365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[101] In 1993, the use of HFCs in foam production began, and

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[100] Emissions of ODSs are not included here consistent with UNFCCC reporting guidelines for national inventories noted in Box 4-1. See Annex 6.2 for more details on emissions of ODSs.

[101] R-404A contains HFC-125, HFC-143a, and HFC-134a.

in 1994 ODS substitutes for halons entered widespread use in the United States as halon production was phased out. In 1995, these compounds also found applications as solvents.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 176.3 MMT CO_2 Eq. emitted in 2020. This increase was in large part the result of efforts to phase out CFCs, HCFCs, and other ODSs in the United States. Use and emissions of HFCs are expected to start decreasing in the next few years and continue downward as production and consumption of HFCs are phased down to 15 percent of their baseline levels by 2036 through an allowance allocation and trading program established by EPA. Improvements in recovery practices and the use of alternative gases and technologies, through voluntary actions and in response to potential future regulations under the AIM Act, will also contribute to a reduction in HFC use and emissions.

Table 4-102 presents emissions of HFCs and PFCs as ODS substitutes by end-use sector for 1990 through 2020. The refrigeration and air-conditioning sector is further broken down by sub-sector. The end-use sectors that contributed the most toward emissions of HFCs and PFCs as ODS substitutes in 2020 include refrigeration and air-conditioning (137.7 MMT CO_2 Eq., or approximately 78 percent), aerosols (18.1 MMT CO_2 Eq., or approximately 10 percent), and foams (15.5 MMT CO_2 Eq., or approximately 9 percent). Within the refrigeration and air-conditioning end-use sector residential unitary AC, part of the Residential Stationary Air-conditioning subsector shown below, was the highest emitting end-use (34.3 MMT CO_2 Eq.), followed by large retail food, which is part of the Commercial Refrigeration subsector. Each of the end-use sectors is described in more detail below.

Table 4-102: Emissions of HFCs and PFCs from ODS Substitutes (MMT CO_2 Eq.) by Sector

Sector	1990	2005	2016	2017	2018	2019	2020
Refrigeration/Air Conditioning	+	89.7	126.4	126.9	129.3	133.3	137.7
Commercial Refrigeration	+	15.0	42.8	41.4	40.3	41.1	41.6
Domestic Refrigeration	+	0.2	1.3	1.3	1.4	1.3	1.3
Industrial Process Refrigeration	+	1.9	11.6	12.9	14.1	15.3	16.5
Transport Refrigeration	+	1.6	5.9	6.4	6.9	7.4	7.9
Mobile Air Conditioning	+	67.7	37.4	33.7	31.5	29.3	27.1
Residential Stationary Air Conditioning	+	1.4	21.6	24.8	28.2	31.6	35.7
Commercial Stationary Air Conditioning	+	2.0	5.8	6.3	6.8	7.2	7.6
Aerosols	0.2	10.7	19.6	18.6	17.4	17.8	18.1
Foams	+	4.0	14.7	15.6	16.1	16.0	15.5
Solvents	+	1.7	1.9	1.9	2.0	2.0	2.0
Fire Protection	+	1.1	2.4	2.5	2.6	2.8	2.8
Total	**0.2**	**107.2**	**165.1**	**165.5**	**167.3**	**171.8**	**176.3**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End-uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning and heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout has taken effect, most equipment has been retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A,[102] R-404A, and R-507A.[103] Lower-GWP options such as hydrofluoroolefin (HFO)-1234yf in motor vehicle air-conditioning, R-717 (ammonia) in cold storage and industrial applications, and R-744 (carbon dioxide) and HFC/HFO blends in retail food refrigeration, are also being used. Manufacturers of residential and commercial air conditioning have announced their plans to use HFC-32 and R-454B[104] in the future. These refrigerants are emitted to the atmosphere during equipment operation (as a result of component failure, leaks, and purges), as well as at manufacturing (if charged at the factory), installation, servicing, and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have replaced the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but the industry is using HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most non-medical consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid or roll-on deodorants and finger-pump sprays. The transition away from ODSs in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. Other low-GWP options such as HFO-1234ze(E) are being used as well. These propellants are released into the atmosphere as the aerosol products are used.

Foams

Chlorofluorocarbons and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the *Montreal Protocol*, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds into alternatives such as CO_2 and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce PU appliance, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a, HFC-134a, and CO_2 are used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Low-GWP fluorinated foam blowing agents in use include HFO-1234ze(E) and HCFO-1233zd(E). Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

Chlorofluorocarbons, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-43-10mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized by products, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of these solvents yields fugitive emissions of these HFCs and PFCs.

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[102] R-410A contains HFC-32 and HFC-125.

[103] R-507A, also called R-507, contains HFC-125 and HFC-143a.

[104] R-454B contains HFC-32 and HFO-1234yf.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and import of virgin halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236fa is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23 and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. Fluoroketone FK-5-1-12 is also used as a low-GWP option and 2-BTP is being considered. As fire protection equipment is tested or deployed, emissions of these fire protection agents occur.

Methodology and Time-Series Consistency

A detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that it tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. The Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions from equipment as they leak over time. By aggregating the data for 78 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.9.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The uncertainty analysis quantifies the level of uncertainty associated with the aggregate emissions across the 78 end-uses in the Vintaging Model. In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock (e.g., number of air conditioning units in operation) for the current year or ODS consumption before transition to alternatives began (e.g., in 1985 for most end-uses). Uncertainty was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed.

The most significant sources of uncertainty for the ODS Substitutes source category include the total stock of refrigerant installed in industrial process refrigeration and cold storage equipment, as well as the charge size for technical aerosols using HFC-134a.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-103. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 170.3 and 200.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 3.4 percent below to 14.0 percent above the emission estimate of 176.3 MMT CO_2 Eq.

Table 4-103: Approach 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (MMT CO_2 Eq. and Percent)

Source	Gases	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	176.3	170.3	200.8	-3.4%	+14.0%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter. Category specific QC findings are described below.

The QA/QC and verification process for individual gases and sources in the Vintaging Model includes review against up-to-date market information, including equipment stock estimates, leak rates, and sector transitions to new chemicals and technologies. In addition, comparisons against published emission and consumption sources by gas and by source are performed when available as described further below. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates. The HFCs and PFCs within the unspecified mix of HFCs and PFCs are modelled and verified individually in the same process as all other gases and sources in the Vintaging Model. For the purposes of reporting emissions to protect Confidential Business Information (CBI), some HFCs and PFCs are grouped into an unspecified mix.

Comparison of Reported Consumption to Modeled Consumption of HFCs

Data from EPA's Greenhouse Gas Reporting Program (GHGRP)[105] was also used to perform quality control as a reference scenario check on the modeled net supply of HFCs, which in turn affects the modeled emissions from this source category as specified in *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. To do so, consumption patterns demonstrated through data reported under GHGRP Subpart OO (Suppliers of Industrial Greenhouse Gases) and Subpart QQ (Importers and Exporters of Fluorinated Greenhouse Gases Contained in Pre-Charged Equipment or Closed-Cell Foams) were compared to the modeled demand for new saturated HFCs used as ODS substitutes from the Vintaging Model. The collection of data from suppliers of HFCs enables EPA to calculate the reporters' aggregated net supply–the sum of the quantities of chemical produced or imported into the United States less the sum of the quantities of chemical transformed (used as a feedstock in the production of other

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[105] For the GHGRP data, EPA verifies annual facility-level and company-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015). Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with a number of general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data.

chemicals), destroyed, or exported from the United States.[106] This allows for an overall quality control check on the modeled demand for new chemical in the Vintaging Model as a proxy for total amount supplied, which is similar to net supply, as an input to the emission calculations in the model.

GHGRP data is not used directly to estimate emissions of ODS Substitutes because it does not include complete, publishable information on the sectors or end-uses in which that chemical will be used, so it does not provide the data that would be needed to calculate the source or time that chemical is emitted. Reports to the GHGRP on production and bulk import (Subpart OO) do not currently include any information on expected end-uses. Reports on fluorinated gases used in equipment and foams (Subpart QQ) do include information on the type of product imported or exported. However, this information is confidential and has not been determined to be publishable at the end-use (i.e., product) level. Irrespective of that, the information would not capture the entire market in the United States, unless it could be determined that for any given product there is no domestic production.

Reported Net Supply (GHGRP Top-Down Estimate)

Under EPA's GHGRP, suppliers (i.e., producers, importers, and exporters) of HFCs under Subpart OO began annually reporting their production, transformation, destruction, imports, and exports to EPA in 2011 (for supply that occurred in 2010) and suppliers of HFCs under Subpart QQ began annually reporting their imports and exports to EPA in 2012 (for supply that occurred in 2011). Among other provisions, the AIM Act of 2020 directed EPA to develop a U.S. production baseline and a U.S. consumption baseline and to phase down HFC production and consumption relative to those baselines. Data reported to the GHGRP under Subpart OO are relevant to the production and consumption baselines. The data below include aggregated Subpart OO data for AIM-listed HFCs for reporting years 2011 through 2020 from all companies that reported AIM-listed HFCs, though not all species were reported in each reporting year.

Modeled Consumption (Vintaging Model Bottom-Up Estimate)

The Vintaging Model, used to estimate emissions from this source category, calculates chemical demand based on the quantity of equipment and products sold, serviced and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment and products.[107] It is assumed that the total demand equals the amount supplied by either new production, chemical import, or quantities recovered (often reclaimed) and placed back on the market. In the Vintaging Model, demand for new chemical, as a proxy for consumption, is calculated as any chemical demand (either for new equipment or for servicing existing equipment) that cannot be met through recycled or recovered material.[108] No distinction is made in the Vintaging Model between whether that need is met through domestic production or imports. To calculate emissions, the Vintaging Model estimates the quantity released from equipment over time, which varies by product type as detailed in Annex 3.9. Thus, verifying the Vintaging Model's calculated consumption against GHGRP reported data, which does not provide details on the end-uses where the chemical is used, is not an exact comparison of the Vintaging Model's emission estimates, but is believed to provide an overall check of the underlying data.

There are eleven saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-43-10mee. While some amounts of less-used saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's

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[106] Chemical that is exported, transformed, or destroyed—unless otherwise imported back to the United States—will never be emitted in the United States.

[107] The model builds an inventory of the in-use stock of equipment and products and ODSs and HFCs in each of the sub-applications. Emissions are subsequently estimated by applying annual and disposal emission rates to each population of equipment and products.

[108] The Vintaging Model does not calculate "consumption" as defined under the Montreal Protocol and the AIM Act, because the model includes chemical supplied to pre-charge equipment made overseas and sent to the domestic market and does not include chemical produced or imported in the United States but placed in products shipped to foreign markets.

GHGRP, the data are believed to represent an amount comparable to the modeled estimates as a quality control check.

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches (i.e., reported and modeled) ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines* (which refer to fluorinated greenhouse gas consumption based on supplies as “potential emissions”):

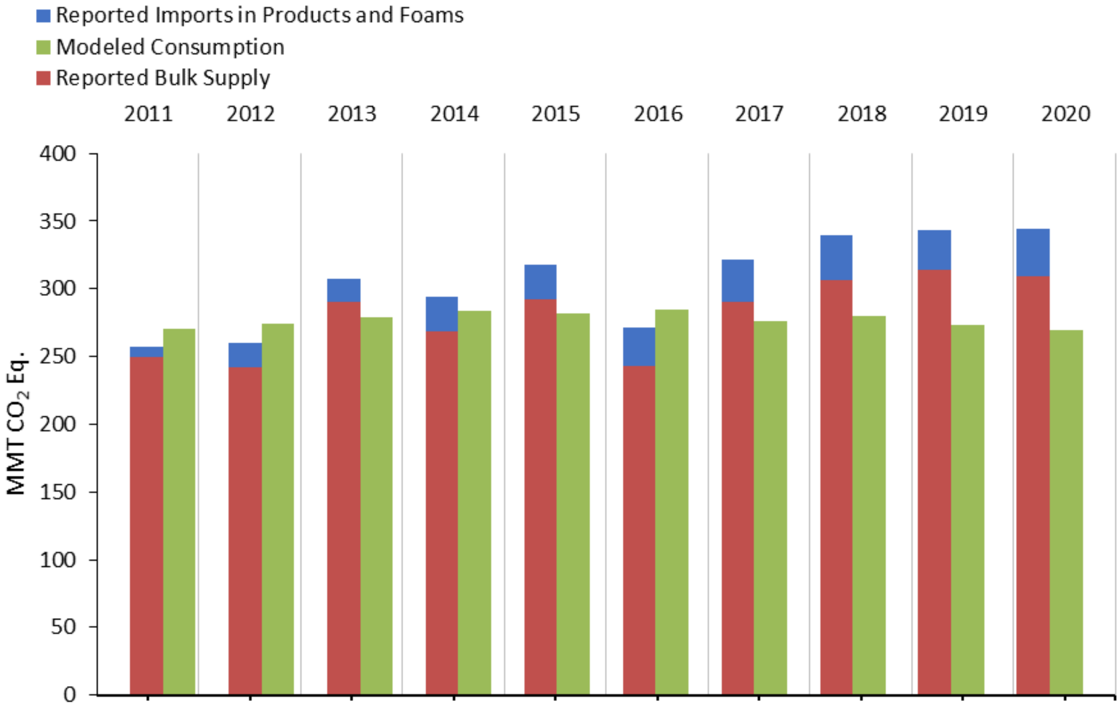
> [W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this ‘potential emissions approach’ per compound with the sum of all activity data of the various uses (IPCC 2006).

Table 4-104 and Figure 4-3 compare the published net supply of saturated HFCs in MMT CO_2 Eq. as determined from Subpart OO (supply of HFCs in bulk) and Subpart QQ (supply of HFCs in products and foams) of EPA’s GHGRP for the years 2011 through 2020 (EPA 2021a; EPA 2022a) and the chemical demand as calculated by the Vintaging Model for the same time series.

Table 4-104: U.S. HFC Supply (MMT CO_2 Eq.)

	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Reported Net Supply (GHGRP)	257	260	307	294	318	271	322	340	344	344
Industrial GHG Suppliers	250	242	290	269	292	243	290	306	314	309
HFCs in Products and Foams	7	18	17	25	26	28	32	34	30	35
Modeled Supply (Vintaging Model)	270	274	279	283	282	285	276	280	273	270
Percent Difference	**5%**	**6%**	**-9%**	**-4%**	**-11%**	**5%**	**-14%**	**-18%**	**-21%**	**-22%**

Figure 4-3: U.S. HFC Consumption (MMT CO_2 Eq.)



As shown, the estimates from the Vintaging Model are lower than the GHGRP estimates by an average of 8.3 percent across the time series (i.e., 2011 through 2020), with the difference growing to an average of 19 percent over the last four years (2017 through 2020). Potential reasons for the differences between the reported and modeled data include:

- The Vintaging Model does not include every saturated HFC that is reported to EPA's GHGRP. Potential improvements in the modeling could include investigation of what sources use and emit such chemicals—which are not necessarily used as ODS substitutes—and to add them into the Inventory. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP data compared to the modeled estimates would be expected.
- Because the top-down data are reported at the time of actual production or import, and the bottom-up data are calculated at the time of actual placement on the market, there could be a temporal discrepancy when comparing data. A potential improvement would be to incorporate a time lag into the model, which would require obtaining data on the movement of supplies through the point of actual use. Because the GHGRP data and the Vintaging Model estimates generally increase over time (although some year-to-year variations exist), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect. Regulations under the AIM Act require the reporting of chemical supplies held at the close of the calendar year; such reports may help investigate this possible factor.
- An additional temporal effect can result from the stockpiling of chemicals by suppliers and distributors. Suppliers might decide to produce or import additional quantities of HFCs for various reasons such as expectations that prices may increase, or supplies may decrease, in the future. Based on information collected by the EPA at the time, such stockpiling behavior was seen during ODS phasedowns, but it is unclear if such behavior exists amongst HFC suppliers in anticipation of current and recently promulgated controls on HFCs. Any such activity would increase the GHGRP data as compared to the modeled data.

This effect may be a major reason why there is a divergence in the comparison above, with the GHGRP data in 2017 through 2020 significantly higher than the modeled data. Similar to above, improvements of the model methodology to incorporate a temporal factor could be investigated. Information on U.S. HFC stockpiles could be used to assess this possible source of discrepancy; however, this data is not collected from suppliers under the GHGRP. Future reporting under the AIM Act may provide useful information in evaluating this issue. Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs or pre-charged equipment and closed-cell foams that contain HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or equal to 25,000 metric tons of CO_2 Eq. per year. Thus, some imports or exports may not be accounted for in the GHGRP data. In 2021, some companies below the reporting threshold for imports and exports reported to the GHGRP, including data from as early as 2011, for AIM-listed HFCs as part of data collection efforts for the U.S. production and consumption baselines; this data is included in the totals presented above. Future reporting under the AIM Act, if released, would likewise be included in the reported totals in the future.

- There could be underreporting to the GHGRP. EPA routinely reviews import data provided by U.S. Customs and Border Protection (CBP) to verify reported supply data and identify facilities that may be subject to the GHGRP. Based on this review and other information, there appeared to be companies that imported or exported more than 25,000 metric tons CO_2 Eq. of HFCs annually that had not reported imports or exports to the GHGRP. Continued enactment and enforcement of the AIM Act is expected to minimize any such information gaps.
- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical or equipment stockpiles as discussed above; in other years, the opposite may hold true. Similarly, relocation of manufacturing facilities or recovery from the recessions and the COVID-19 pandemic could contribute to variability in imports or exports. Averaging net supplies over multiple years can minimize the impact of such fluctuations. For example, when the 2012 and 2013 net additions to the supply are averaged, as shown in Table 4-105, the percent difference between the consumption estimates decreases compared to the 2012-only and 2013-only estimates.

Table 4-105: Averaged U.S. HFC Demand (MMT CO_2 Eq.)

	2011-2012 Avg.	2012-2013 Avg.	2013-2014 Avg.	2014-2015 Avg.	2015-2016 Avg.	2016-2017 Avg.	2017-2018 Avg.	2018-2019 Avg.	2019-2020 Avg.
Reported Net Supply (GHGRP)	259	284	301	306	295	297	331	342	344
Modeled Demand (Vintaging Model)	272	277	281	283	283	280	278	276	271
Percent Difference	**5%**	**-2%**	**-6%**	**-8%**	**-4%**	**-6%**	**-16%**	**-19%**	**-21%**

- The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects demand increasing or decreasing slowly, with some annual fluctuations, actual consumption for specific chemicals or equipment may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, and destroyed than produced and imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by recovery of HFCs from equipment that is being disposed. If, in any given year, a significant number of units are disposed, there will be a large amount of additional recovery in that year that can cause an unexpected and not modeled decrease in demand and thus a decrease in consumption. On the other hand, if market, economic, or other factors cause less than expected disposal or recovery, actual supply would decrease, and hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP amounts. EPA has published reclamation data, which would encompass a portion of the refrigerant recovered annually. This data could be reviewed to determine if it can be used to improve the modeling of these factors.

- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, all equipment or products that contain ODSs or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like equipment or products originally produced in the United States. The GHGRP data from Subpart OO (industrial greenhouse gas suppliers) includes HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. The GHGRP data from Subpart QQ (supply of HFCs in products) accounts for most of these differences; however, the scope of Subpart QQ does not cover all such equipment or products and the chemical contained therein. Depending on whether the United States is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence for some years possibly higher than GHGRP data:

- Saturated HFCs are also known to be used and emitted from other sources, such as electronics manufacturing and magnesium production and processing. The Vintaging Model estimates here do not include the amount of HFCs used for these applications, but rather only the amount used for applications that traditionally were served by ODSs. Nonetheless, EPA expects the quantities of HFCs used for electronics and magnesium production to be very small compared to the ODS substitute use for the years analyzed. EPA estimates that electronics and magnesium production respectively consumed 0.8 MMT CO_2 Eq. and 0.1 MMT CO_2 Eq. of HFCs in 2019, which is much less than the ODS substitute sector in that year (170 MMT CO_2 Eq.) (U.S. EPA 2021b).

Comparison of Emissions Derived from Atmospheric Measurements to Modeled Emissions

Emissions of some fluorinated greenhouse gases are estimated for the contiguous United States from the National Oceanic and Atmospheric Administration (NOAA) and were used to perform additional quality control by comparing the emission estimates derived from atmospheric measurements by NOAA to the bottom-up emission estimates from the Vintaging Model. The *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) Volume 1: General Guidance and Reporting, Chapter 6: Quality Assurance, Quality Control and Verification notes that atmospheric concentration measurements can provide independent data sets as a basis for comparison with inventory estimates. Further, it identified fluorinated gases as one of most suitable greenhouse gases for such comparisons. The *2019 Refinement* makes this conclusion on fluorinated gases based on the lack of natural sources, the potential uncertainties in bottom-up inventory methods for some sources, the long life of many of these gases, and the well-known loss mechanisms. Unlike most other gases in the Inventory, since there are no known natural sources of HFCs, the HFC emission sources included in this Inventory account for the majority of total emissions detectable in the atmosphere, and the estimates derived from atmospheric measurements are driven solely by anthropogenic emissions.

The *2019 Refinement* provides guidance on conducting such comparisons (as summarized in Table 6.2 of IPCC 2019 Volume 1, Chapter 6) and provides guidance on using such comparisons to identify areas of improvement in national inventories (as summarized in Box 6.5 of IPCC 2019 Volume 1, Chapter 6).

Emission estimates for four key HFCs from Hu et al. (2017) were used in this comparison. This provides a quality check on the modeled emissions reported above. Hu et al. (2017) provided similar comparisons; here the EPA data used in Hu et al. was updated to reflect the current Inventory estimates. Potential Inventory updates identified due to the comparison with atmospheric data are noted in the Planned Improvements section below.

Comparison of Results

Table 4-106 lists the emissions NOAA derived for the contiguous United States from atmospheric measurements as described in Hu et al. (2017) and those from EPA's Vintaging Model. Figure 4-4 and Figure 4-5 below show this information graphically. Specifically, the data compared are emissions of HFC-32, HFC-125 and HFC-143a (Table 4-106 and Figure 4-4) and emissions of HFC-134a (Table 4-106 and Figure 4-5) for the years covered in Hu et al., i.e., 2008 through 2014. In the Supplemental Information, Hu et al. (2017) provided uncertainty results representing one standard deviation of the spread of several inversion calculations. These are provided in the tables and figures below. There is also uncertainty in the EPA results. Overall, the uncertainty in EPA's total Substitution of ODS emissions range from -3.4 percent to 14.0 percent (95 percent confidence interval), as shown above. The nature of the model and the uncertainty analysis, however, does not allow EPA to provide specific uncertainties to each species and hence comparisons below are to the EPA estimates without consideration of the uncertainty involved in those estimates.

Table 4-106: U.S. Emissions of HFC-32, HFC-125, HFC-134a and HFC-143a (Gg)

Gas	Source	2008	2009	2010	2011	2012	2013	2014
HFC-32	NOAA	1.65±0.34	2.12±0.44	2.87±0.44	3.33±0.66	3.75±0.43	4.26±0.44	5.05±0.86
	EPA	1.22	1.56	2.17	2.78	3.44	4.19	5.00
HFC-125	NOAA	7.05±1.68	6.52±1.52	7.91±1.37	7.92±1.29	7.79±0.85	8.79±1.05	9.77±1.40
	EPA	5.02	6.05	7.22	8.34	9.37	10.41	11.43
HFC-134a	NOAA	49.14±11.05	42.11±9.59	49.81±6.46	40.45±6.90	37.63±3.23	40.80±5.19	42.81±5.97
	EPA	60.43	62.27	62.32	59.35	56.34	53.20	52.06
HFC-143a	NOAA	4.94±1.22	4.07±1.13	4.95±0.94	3.97±0.59	3.65±0.31	4.18±0.63	5.34±0.84
	EPA	3.42	3.99	4.52	4.99	5.40	5.75	6.01

Note: NOAA uncertainty values represent one standard deviation

Figure 4-4: U.S. Emissions of HFC-32, HFC-125, and HFC-143a

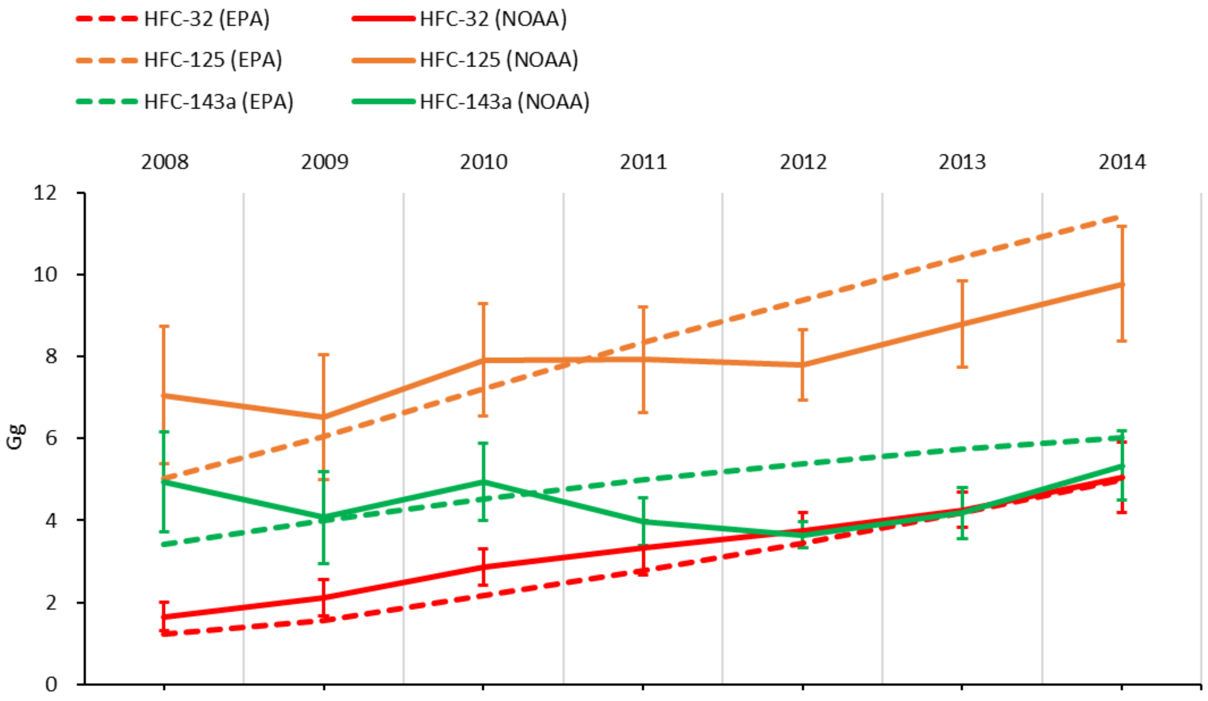
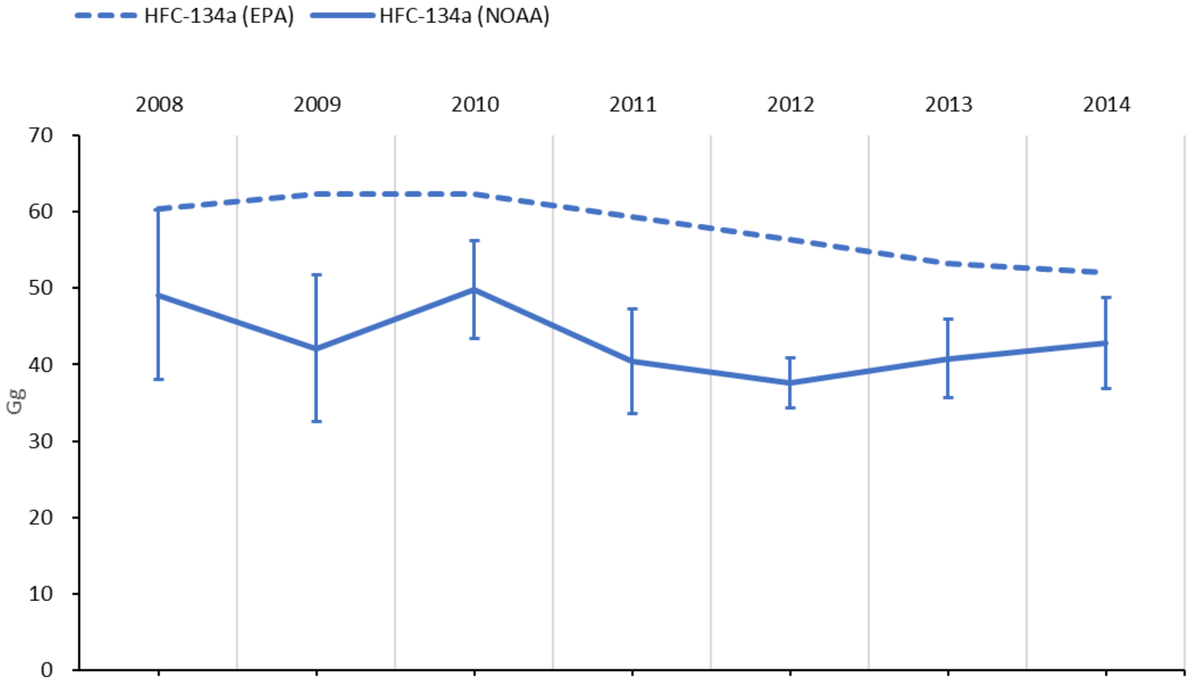


Figure 4-5: U.S. Emissions of HFC-134a



As shown, modeled estimates of HFC-32 are comparable with those derived from atmospheric measurements, with only small differences (in Gg y^{-1}). The modeled estimates for 2011 to 2014 lie within the one standard deviation (1 s.d.) uncertainty range of the atmospherically derived estimates after 2010, and both datasets show a similar trend of year-on-year increasing emissions, reaching ~5 Gg y^{-1} by 2014. On the other hand, modeled emissions of HFC-134a were consistently higher than those seen through atmospheric measurements, well above the one standard deviation uncertainty. While the mean values from NOAA show year-to-year variability, the data may suggest a slight downward trend in HFC-134a emissions through this entire period, like the modeled result; however, confidence in the trend from atmospheric measurements is limited because the magnitude of uncertainties are similar to the overall change and because increasing or decreasing trends of the mean values do not persist for more than two years. The magnitude and time-dependence of the differences for both HFC-125 and HFC-143a were similar, as results from this inventory model were lower in 2008 through 2010 and higher in 2011 through 2014, compared to the means estimated by NOAA. Considering the uncertainty ranges, the modeled results for HFC-125 agree for the years 2009 to 2011, and those for HFC-143a agree for 2009 to 2010 and 2014. The modeled results trend upward year-on-year for both gases, although the increase is smaller for HFC-143a. In the NOAA estimates, no secular trend is discernable from 2008 to 2014 for HFC-143a considering the annual mean uncertainties of approximately 18 percent. NOAA results for HFC-125 have similar uncertainty magnitudes but may suggest a small increase in emissions over time, particularly in the latter years during this time interval.

Table 4-107 shows the differences in the emissions results from EPA's Vintaging Model and the mean results from NOAA for those years where modeled estimates were not within the given 1 s.d. uncertainty range in the NOAA results. Years when modeled estimates are within the uncertainty range reported by NOAA are not shown as those differences are assumed to be insignificant. Because the uncertainty represents several inversion calculations, a formally estimated 2 s.d. uncertainty range is not available. Instead, EPA considers twice the uncertainty estimated by NOAA, which represents a range that is larger than the actual 2 s.d. from the spread of inversions. Emissions differences found to be outside that range are shown in bold in the table, indicating more attention may be warranted to understand these results. Comparing the results from the individual gases shows changes over time, for example:

a. For HFC-32, while the difference was greater than 20 percent prior to 2011 compared to the mean values, the difference from the 1 s.d. amounts averaged only 0.16 Gg during these three years. These differences are insignificant at the twice uncertainty level. Results were within the 1 s.d. uncertainty range of the NOAA estimates starting in 2011.

b. For HFC-125, the difference was within the uncertainty range of the NOAA estimates from 2009 to 2011, but greater than 15 percent of the mean values for 2008 (model results lower) and after 2011 (model results higher). All results were within the twice uncertainty range.

c. For HFC-134a, the differences ranged from 22 percent (in 2014) to 50 percent (in 2012), with all modeled estimates higher than the NOAA estimates even when the 1 s.d. uncertainty ranges were considered. For this gas, only the 2008, 2010, and 2014 estimates were within the NOAA estimates at twice the uncertainty.

d. For HFC-143a, the modeled results were within the uncertainty range in 2009 to 2010 and again in 2014. The 2008 and 2011 model results were within the twice uncertainty range. For 2008, the modeled results were below the uncertainty range by 31 percent compared to the mean value, whereas for 2011 to 2013 the modeled results were above the uncertainty ranges, by an average of 37 percent compared to the mean values.

Table 4-107: Percentage Differences between EPA and NOAA HFC Emission Estimates

Year	HFC-32	HFC-125	HFC-134a	HFC-143a
2008	-0.43 (-26%)	-2.0 (-29%)	11.3 (23%)	-1.5 (-31%)
2009	-0.56 (-26%)		**20.2 (48%)**	
2010	-0.70 (-25%)		12.5 (25%)	
2011			**18.9 (47%)**	1.0 (26%)
2012		1.6 (20%)	**18.7 (50%)**	**1.7 (48%)**
2013		1.6 (18%)	**12.4 (30%)**	**1.6 (37%)**
2014		1.7 (17%)	9.3 (22%)	
Average	-0.57 (-15%)	0.7 (7%)	14.8 (35%)	0.7 (20%)
Average of Absolute Values	26%	17.3 (21%)	14.8 (35%)	14.6 (36%)

Notes: Differences smaller than the 1 s.d. uncertainty on the annual NOAA-based estimates are not shown. Differences greater than 2 s.d. shown in bold font. Uncertainties associated with the Vintaging model have not been estimated by compound and year so are not included and could imply fewer differences than shown in this table.

Discussion and Areas for Additional Research

The following are potential contributing factors to the variation between the results and possible ways these could inform changes to the model that would reduce the differences seen.

- When examining the NOAA estimates with twice the uncertainties provided, only a few of these larger differences from EPA model results are identified. The uncertainties in the NOAA estimates are primarily driven by the frequency and spatial density of the atmospheric sampling, and the transport model simulations. There is also inherent uncertainty in the consistency of the setup of each gas chromatography measurement taken–e.g., variation in calibration, impurities in the carrier gas used, among others (Barwick 1999); however, that uncertainty is likely less than 1 percent for HFC-125, HFC-134a, and HFC-143a, and less than 5 percent for HFC-32. Given the magnitude of the uncertainties relative to the size of any apparent emission changes, and the limited time period of the analysis, overall trends in most of the gases are hard to discern with confidence except in the case of HFC-32. Although NOAA estimates are derived from thousands of individual sample analyses (approximately 5,000 per year), continued analysis and additional years will enable a better understanding of any secular trends in the NOAA-derived estimates, and hence whether the modeled results are showing similar changes over time.

As discussed above, there is also uncertainty in the EPA estimates. Although these are not available by individual species, these uncertainties may also explain some of the differences seen.

- A thorough discussion of the uncertainties and influencing factors in the NOAA estimates is provided in Hu et al. (2017). That study notes that emissions estimated from inverse modeling of atmospheric data can depend on assumed prior emission distributions and magnitudes, and accordingly the quoted uncertainties on the NOAA results have been augmented to include these influences. In general, in a region where there are fewer atmospheric observations, the NOAA results will inherently tend towards the prior and be impacted by neighboring regions and populations (NOAA/EPA 2020). If the emissions or emissions per person (depending on which prior is used) are significantly different in these areas compared to the nearby areas, derived emissions for these regions can be biased.
- Uncertainty in atmospheric emission estimates is influenced by the number of NOAA's atmospheric sampling sites, which changed between 2008 and 2014. Uncertainties were greatest in 2008 and 2009—i.e., early on in the North American sampling program (Hu et al. 2017)—due to a fewer number of tower sites and available measurements in those startup years. This may help explain why none of the EPA results for 2008 were within one standard deviation of the NOAA estimates, but all were within twice the uncertainty range. Also, changes in the number and location of measurement sites within the air sampling network containing over 25 sites can lead to biases in the year-to-year emission estimates. During the 2008 to 2014 period addressed by Hu et al. (2017), measurements at four network sites began only after 2008, while observations at two others were terminated. Uncertainties related to network changes were estimated with separate inversion runs in which sites were removed from the analysis and differences ascertained. These influences contribute to the uncertainties quoted on the NOAA estimates, as do the uncertainties related to meteorological models.
- The Vintaging Model estimated emissions for the entire United States, including all 50 states and territories. Conversely, NOAA limits scope to the contiguous 48 states and the District of Columbia (NOAA/EPA 2020). In that regard, EPA would expect the model to estimate slightly higher emissions than those reported by NOAA, by roughly 2 percent based on population data (U.S. Census 2021). Activity data for Hawaii, Alaska and territories could be researched. If available, calculations to reduce the bottom-up results could be made and the results compared again to the NOAA results.
- For HFC-125 and HFC-143a, the EPA model suggests lower emissions in 2008 and higher in 2012 to 2013 relative to the atmosphere-derived estimates. Further research into the refrigeration market might improve the agreement in the estimates for these two gases. As stated in the Introduction above, emissions from the large retail food end-use (e.g., supermarkets), which uses both these gases, were estimated to have the second highest contribution to the overall HFC emissions. Research in this industry on the shift away from blends such as R-404A (which contains both HFC-125 and HFC-143a) or success in lowering emission rates could be used to improve the bottom-up model.
- The modeled emissions of HFC-32 agreed well with the atmospheric inversion results in absolute terms, and both data sets showing the same year-on-year increasing trend. Irrespective of the uncertainties, slightly lower model results might imply that the model assumed a higher than actual use of "dry-charge" residential AC equipment in lieu of R-410A (a 50:50 by mass ratio of HFC-32 and HFC-125). It might also mean the actual emissions from R-410A equipment were slightly higher than modeled.
- The modeled inventory results for HFC-134a are complicated by an assumed decrease in emissions from motor vehicle air conditioning (due to previous shifts towards lower charge sizes and emission rates, as well as the on-going transition to HFO-1234yf) with concurrent increases in other sectors, such as for foam blowing given the HCFC bans in foam blowing and other uses. Even though the NOAA results may also suggest an increase from 2012 to 2014, the magnitudes of uncertainties prevent a robust conclusion of emission increases over this period. While the inter-annual changes in the NOAA mean values for this gas are small compared to the uncertainties, they are not inconsistent with the slow rate of increase followed by a slow rate of decrease seen in the modeled emissions during 2008 through 2014. If the model is overestimating the increased use in foam blowing and/or underestimating the decrease in

emissions from the motor vehicle air conditioning end-use, that might account for some of the differences seen.

- In addition to its use as an ODS substitute, HFC-134a is used in a cover gas to prevent oxidation during magnesium metal production and in semiconductor manufacturing. EPA's Vintaging Model does not include these possible emission sources of HFC-134a, which, if included, would increase the difference between the model-based result and NOAA's. The use and emissions of HFC-134a from these sources are small (see above and elsewhere in this Inventory), so this would not be a significant contribution to the comparison above.
- There are data limitations inherent in the bottom-up model. As described above, emissions are estimated by applying assumed emission profiles to multiple end-uses, each of which can have thousands or millions of individual uses in the United States. In some cases where equipment stocks or sales are unknown, estimates are made using an average growth rate and by taking the most recent year where the starting stock or sales of equipment is known, then accounting for equipment lifetimes, and subsequently estimating the amount of equipment in future and/or preceding years where a value was not available. Such assumptions are evident in the approximately constant slope of the EPA emission estimates for HFC-32, HFC-125, and HFC-143a, compared to the more varying nature found in NOAA's mean results. Except for HFC-32, which shows year-on-year increases across both sets of estimates, trends in the NOAA-derived emissions are typically small relative to uncertainty magnitudes in measured data. Future work could look at whether these variations might be consistent with other factors that influence emissions, such as equipment installations, sales, or retirements, which could vary from year to year.

Using a Tier 2 bottom-up modeling methodology to estimate emissions requires assumptions and expert judgment. Comparing the Vintaging Model's estimates to GHGRP-reported estimates of supply shown above and emissions estimates derived from atmospheric measurements, particularly for more widely used chemicals, can help validate the model but it is expected that the model will have limitations. These comparisons show that Vintaging Model consumption estimates are well within the same order of magnitude as the actual consumption data as reported to EPA's GHGRP although the differences in reported net supply and modeled demand are still significant. Likewise, these comparisons show reasonable agreement with atmospheric measurement derivations of emissions, though certain chemicals and during certain years differences can be significant. Hence, areas for further research that may improve the modeling are highlighted above. Despite the strengths and weaknesses of three independent approaches for estimating emissions of these HFCs, the reasonable agreement noted here in most instances provides added confidence in EPA's understanding of total U.S. emissions for these chemicals and how they've change over time and, furthermore, has helped identify areas for potential improvement in the future.

Recalculations Discussion

For the current Inventory, updates to the Vintaging Model included updating market size, manufacturing loss rate, disposal loss rate, and post-life emission rate assumptions for various PU foam end-uses to align with market research (EPA 2021c). Growth rates for window units were updated to align with sales data for Energy Star- and non-Energy Star-certified units and a transition to HFC-32 was implemented beginning in 2015 to reflect manufacturer transitions (EPA 2022b). In addition, HFC consumption for MDIs was updated to align with an analysis of MDI sales in the United States (EPA 2022c). Together, these updates decreased ODS substitute emissions on average by 0.03 MMT CO_2 Eq. (0.004 percent) between 1990 and 2019.

Planned Improvements

Future improvements to the Vintaging Model are planned for the Fire Suppression and Aerosols sectors. Specifically, streaming agent fire suppression lifetimes, market size, and growth rates are under review to align more closely with real world activities. In addition, further refinement of HFC consumption in MDIs is expected from review of data collected on HFC use for MDI production, imports, and exports in response to requests for application-specific allowances for MDIs. EPA expects these revisions to be prepared for the 2023 or 2024 Inventory submission.

EPA has identified several updates to the Vintaging Model based on regularly published or released data that will be implemented in the Vintaging Model on an annual basis, including updating growth rates for residential and commercial unitary air-conditioning to align with annual sales estimates published by AHRI and for window units to align with sales data released by EPA's Energy Star Program. In addition, as future application-specific allocations for MDIs are granted, EPA will ensure the Vintaging Model is in alignment. Implemented updates are expected to have a lagging effect on Inventory estimates (i.e., 2021 data published in 2022 will appear in the 2023 Inventory submission) and will therefore not be explicitly discussed in the Recalculations Discussion.

As discussed above, future reporting under the AIM Act may provide useful information for verification purposes and possible improvements to the Vintaging Model. EPA expects this reporting by early 2023 and incorporation into the 2024 or 2025 report. Should the data suggest structural changes to the model, such as the handling of stockpiles before use, EPA expects to introduce the revised model for the 2025 or 2026 Inventory submission.

Several potential improvements to the Inventory were identified based on the comparison with atmospheric data. To improve estimates of HFC-125 and HFC-143a, further research into the refrigeration market can be made. Research in this industry on the shift away from blends such as R-404A or success in lowering emission rates could be used to improve the Inventory estimate. This is planned for the 2024 Inventory cycle. Slightly lower model results for HFC-32 might imply that the model assumed a higher than actual use of "dry-charge" residential AC equipment in lieu of R-410A; EPA plans to investigate the amount of "dry-charge" AC imports during the 2023 Inventory cycle. Uncertainty estimates by species would aid in comparisons to atmospheric data. EPA will explore the possibility of revising the Monte Carlo analysis to differentiate between species, staring with the higher-emitted HFCs identified above, in a future (i.e., 2024 or 2025) Inventory submission.

4.25 Electrical Transmission and Distribution (CRF Source Category 2G1)

The largest use of sulfur hexafluoride (SF_6), both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. SF_6 has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas. Another greenhouse gas emitted in much smaller amounts by the electric power industry is tetrafluoromethane (CF_4), which is mixed with SF_6 to avoid liquefaction at low temperatures (Middleton 2000). While mixed gas circuit breakers are more common in extremely cold climates in geographies outside of the United States, some U.S. manufacturers of electrical equipment are emitting CF_4 during the manufacturing of equipment designed to hold the SF_6/CF_4 gas mixture. However, no electrical transmission and distribution facilities in the United States have reported emissions of or equipment using CF_4. SF_6 emissions exceed PFC emissions from electric power systems on both a GWP-unweighted and GWP-weighted basis.

Fugitive emissions of SF_6 and CF_4 can escape from gas-insulated substations and switchgear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF_6 and CF_4 from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 3.8 MMT CO_2 Eq. (0.2 kt) in 2020. This quantity represents an 84 percent decrease from the estimate for 1990 (see Table 4-108 and Table 4-109). There are a few potential causes for this decrease: a sharp increase in the price of SF_6 during the 1990s and a growing awareness of the environmental impact of SF_6 emissions through programs such as EPA's voluntary SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership) and EPA's GHGRP, regulatory drivers at the state and local levels, and research and development of alternative gases to SF_6 that can be used in gas-insulated substations.

Utilities participating in the Partnership have lowered their emission factor from 13 percent in 1999 (kg SF_6 emitted per kg of nameplate capacity) to 1 percent in 2020. A recent examination of the SF_6 emissions reported by electric power systems to EPA's GHGRP revealed that SF_6 emissions from reporters have decreased by 48 percent from 2011 to 2020,[109] with much of the reduction seen from utilities that are not participants in the Partnership. These utilities may be making relatively large reductions in emissions as they take advantage of relatively large and/or inexpensive emission reduction opportunities (i.e., "low hanging fruit," such as replacing major leaking circuit breakers) that Partners have already taken advantage of under the voluntary program (Ottinger et al. 2014). Total emissions from electrical transmission and distribution in 2020 were lower than 2019 emissions, decreasing by 11.7 percent. The decrease in emissions may be attributed to a decrease in the average emission rate reported to the GHGRP in 2020.

Table 4-108: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (MMT CO_2 Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	22.8	0.3	**23.2**
2005	7.7	0.7	**8.4**
2016	3.8	0.2	**4.1**
2017	3.9	0.3	**4.2**
2018	3.6	0.3	**3.8**
2019	3.9	0.3	**4.2**
2020	3.3	0.5	**3.8**

Note: Totals may not sum due to independent rounding.

Table 4-109: SF_6 and CF_4 Emissions from Electric Power Systems and Electrical Equipment Manufacturers (kt)

Year	SF_6 Emissions	CF_4 Emissions
1990	1.0	NO
2005	0.4	0.00032
2016	0.2	0.00004
2017	0.2	+
2018	0.2	NO
2019	0.2	0.00006
2020	0.2	0.00002

+ Does not exceed 0.000005 kt.
NO (Not Occurring)

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[109] Analysis of emission trends from facilities reporting to EPA's GHGRP is imperfect due to an inconsistent group of reporters year to year. A facility that has reported total non-biogenic greenhouse gas emissions below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years to EPA's GHGRP can discontinue reporting for all direct emitter subparts. For this sector, most of the variability in the group of reporters is due to facilities exiting the GHGRP due to being below one of these thresholds; however, facilities must re-enter the program if their emissions at a later date are above 25,000 MT CO_2 Eq., which may occur for a variety of reasons, including changes in facility size and changes in emission rates.

Methodology and Time-Series Consistency

The estimates of emissions from Electrical Transmission and Distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1990 through 1998 Emissions from Electric Power Systems

Emissions from electric power systems from 1990 through 1998 were estimated based on (1) the emissions estimated for this source category in 1999, which, as discussed in the next section, were based on the emissions reported during the first year of EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partnership), and (2) the RAND survey of global SF_6 emissions. Because most utilities participating in the Partnership reported emissions only for 1999 through 2011, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 through 1999 period. To estimate global emissions, the RAND survey of global SF_6 sales was used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the *2006 IPCC Guidelines*.[110] (Although Equation 7.3 of the *2006 IPCC Guidelines* appears in the discussion of substitutes for ozone-depleting substances, it is applicable to emissions from any long-lived pressurized equipment that is periodically serviced during its lifetime.)

Equation 4-23: Estimation for SF_6 Emissions from Electric Power Systems

$$\text{Emissions (kilograms } SF_6\text{)} = SF_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity of retiring equipment (kilograms)}$$[111]

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1999.

U.S. emissions between 1990 and 1999 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 13.6 MMT CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal

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[110] Ideally, sales to utilities in the United States between 1990 and 1999 would be used as a model. However, this information was not available. There were only two U.S. manufacturers of SF_6 during this time period, so it would not have been possible to conceal sensitive sales information by aggregation.

[111] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey and is not accounted for in any another manner by RAND. However, atmospheric studies confirm that the downward trend in estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1999 through 2020 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2020 were estimated based on: (1) reporting from utilities participating in EPA's SF_6 Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; (2) reporting from utilities covered by EPA's GHGRP, which began in 2012 for emissions occurring in 2011 (GHGRP-Only Reporters); and (3) the relationship between utilities' reported emissions and their transmission miles as reported in the 2001, 2004, 2007, 2010, 2013, and 2016 Utility Data Institute (UDI) Directories of Electric Power Producers and Distributors (UDI 2001, 2004, 2007, 2010, 2013, and 2017), and 2019 and 2020 Homeland Infrastructure Foundation-Level Data (HIFLD) (HIFLD 2019 and 2020), which was applied to the electric power systems that do not report to EPA (Non-Reporters). Total U.S. Transmission mileage was interpolated between 2016 and 2019 to estimate transmission mileage of electric power systems in 2017 and 2018. (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV).

Partners

Over the period from 1999 to 2020, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership,[112] represented 49 percent, on average, of total U.S. transmission miles. Partner utilities estimated their emissions using a Tier 3 utility-level mass balance approach (IPCC 2006). If a Partner utility did not provide data for a particular year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2012, many Partners began reporting their emissions (for 2011 and later years) through EPA's GHGRP (discussed further below) rather than through the Partnership. In 2020, approximately 1 percent of the total emissions attributed to Partner utilities were reported through Partnership reports. Approximately 99 percent of the total emissions attributed to Partner utilities were reported and verified through EPA's GHGRP. Partners without verified 2020 data accounted for less than 1 percent of the total emissions attributed to Partner utilities.[113]

The GHGRP program has an "offramp" provision (40 CFR Part 98.2(i)) that exempts facilities from reporting under certain conditions. If reported total greenhouse gas emissions are below 15,000 metric tons of carbon dioxide equivalent (MT CO_2 Eq.) for three consecutive years or below 25,000 MT CO_2 Eq. for five consecutive years, the facility may elect to discontinue reporting. GHGRP reporters that have off-ramped are extrapolated for three years of non-reporting using a utility-specific transmission mile growth rate. After three consecutive years of non-reporting, they are treated as non-reporters, as described in the section below on non-reporters. Partners that have years of non-reporting between reporting years are gap filled by interpolating between reported values.

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[112] Starting in the 1990 to 2015 Inventory, partners who had reported three years or less of data prior to 2006 were removed. Most of these Partners had been removed from the list of current Partners but remained in the Inventory due to the extrapolation methodology for non-reporting partners.

[113] Only data reported as of August 7, 2021 are used in the emission estimates for the prior year of reporting. Emissions for Partners that did not report to the Partnership or GHGRP are extrapolated for three years using a utility-specific transmission mile growth rate. After four consecutive years of non-reporting they are included in the 'non-reporting Partners' category. It should be noted that data reported through EPA's GHGRP must go through a verification process. For electric power systems, verification involved a series of electronic range, completeness, and algorithm checks for each report submitted.

GHGRP-Only Reporters

EPA's GHGRP requires users of SF_6 in electric power systems to report emissions if the facility has a total SF_6 nameplate capacity that exceeds 17,820 pounds. (This quantity is the nameplate capacity that would result in annual SF_6 emissions equal to 25,000 metric tons of CO_2 equivalent at the historical emission rate reported under the Partnership.) As under the Partnership, electric power systems that report their SF_6 emissions under EPA's GHGRP are required to use the Tier 3 utility-level mass-balance approach. Many Partners began reporting their emissions through EPA's GHGRP in 2012 (reporting emissions for 2011 and later years) because their nameplate capacity exceeded the reporting threshold. Some Partners who did not report through EPA's GHGRP continued to report through the Partnership.

In addition, many non-Partners began reporting to EPA for the first time through its GHGRP in 2012. Non-Partner emissions reported and verified under EPA's GHGRP were compiled to form a new category of reported data (GHGRP-Only Reporters). GHGRP-Only Reporters accounted for 17 percent of U.S. transmission miles and 24 percent of estimated U.S. emissions from electric power system in 2020.[114]

Emissions for GHGRP-only reporters that off-ramp are extrapolated for three years of non-reporting using a utility-specific annual transmission mile growth rate. After three consecutive years of non-reporting, they are treated as non-reporters, and emissions are subsequently estimated based on the methodology described below.

Non-Reporters

Emissions from Non-Reporters (i.e., utilities other than Partners and GHGRP-Only Reporters) in every year since 1999 were estimated using the results of a regression analysis that correlated emissions from reporting utilities (using verified data from both Partners and GHGRP-Only Reporters) with their transmission miles.[115] As noted above, non-Partner emissions were reported to the EPA for the first time through its GHGRP in 2012 (representing 2011 emissions). This set of reported data was of particular interest because it provided insight into the emission rate of non-Partners, which previously was assumed to be equal to the historical (1999) emission rate of Partners. Specifically, emissions were estimated for Non-Reporters as follows:

- Non-Reporters, 1999 to 2011: First, the 2011 emission rates (per kg nameplate capacity and per transmission mile) reported by Partners and GHGRP-Only Reporters were reviewed to determine whether there was a statistically significant difference between these two groups. Transmission mileage data for 2011 was reported through GHGRP, with the exception of transmission mileage data for Partners that did not report through GHGRP, which was obtained from UDI. It was determined that there is no statistically significant difference between the emission rates of Partners and GHGRP-Only reporters; therefore, Partner and GHGRP-Only reported data for 2011 were combined to develop regression equations to estimate the emissions of Non-Reporters. Historical emissions from Non-Reporters were estimated by linearly interpolating between the 1999 regression coefficient (based on 1999 Partner data) and the 2011 regression coefficient.
- Non-Reporters, 2012 to Present: The emissions data from Partners and by GHGRP-Only Reporters were combined to develop regression equations for 2012. This was repeated for 2013 through 2020 using Partner and GHGRP-Only Reporter data for each year.
    - The 2020 regression equation for reporters was developed based on the emissions reported by a subset of Partner utilities and GHGRP-Only utilities who reported non-zero emissions and non-zero

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[114] GHGRP-reported and Partner transmission miles from a number of facilities were equal to zero with non-zero emissions. These facilities emissions were added to the emissions totals for their respective parent companies when identifiable and not included in the regression equation when not identifiable or applicable. Other facilities reported non-zero transmission miles with zero emissions, or zero transmission miles and zero emissions. These facilities were not included in the development of the regression equations (discussed further below). These emissions are already implicitly accounted for in the relationship between transmission miles and emissions.

[115] In the United States, SF_6 is contained primarily in transmission equipment rated above 34.5 kV.

transmission miles (representing approximately 62 percent of total U.S. transmission miles). The regression equation for 2020 is:

Equation 4-24: Regression Equation for Estimating SF_6 Emissions of Non-Reporting Facilities

$$\text{Emissions (kg)} = 0.186 \times \text{Transmission Miles}$$

Table 4-110 below shows the percentage of transmission miles covered by reporters (i.e., associated with reported data) and the regression coefficient for 1999 (the first year data was reported), and for 2011 through present (the years with GHGRP reported data). The coefficient decreased between 2016 and 2020.

Table 4-110: Transmission Mile Coverage (Percent) and Regression Coefficients (kg per mile)

	1999	2005	2016	2017	2018	2019	2020
Percentage of Miles Covered by Reporters	50%	50%	72%	73%	72%	66%	62%
Regression Coefficient[a]	0.71	0.35	0.21	0.25	0.21	0.23	0.19

[a] Regression coefficient for emissions is calculated utilizing transmission miles as the explanatory variable and emissions as the response variable. The equation utilizes a constant intercept of zero. When calculating the regression coefficient, outliers are also removed from the analysis when the standard residual for that reporter exceeds the value 3.0.

Data on transmission miles for each Non-Reporter for the years 2000, 2003, 2006, and 2009, 2012, and 2016 were obtained from the 2001, 2004, 2007, 2010, 2013, and 2017 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007, 2010, 2013, and 2017). For 2019 and 2020, non-reporter transmission mileage was derived by subtracting reported transmission mileage data from the total U.S. transmission mileage from 2019 and 2020 HIFLD Data (HIFLD 2019 and 2020). The following trends in transmission miles have been observed over the time series:

- The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 yet declined by almost 4,000 miles between 2003 and 2006. Given these fluctuations, periodic increases are assumed to occur gradually. Therefore, transmission mileage was assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and decrease by 0.20 percent between 2003 and 2006.
- The U.S. transmission system's annual growth rate grew to 1.7 percent from 2006 to 2009 as transmission miles increased by more than 33,000 miles.
- The annual growth rate for 2009 through 2012 was calculated to be 1.5 percent as transmission miles grew yet again by over 30,000 miles during this time period.
- The annual transmission mile growth rate for 2012 through 2016 was calculated to be 0.4 percent, as transmission miles increased by approximately 10,250 miles.
- The annual transmission mile growth rate for 2016 through 2019 was calculated to be 0.9 percent, as transmission miles increased by approximately 19,900 miles.
- The annual transmission mile growth rate for 2019 through 2020 was calculated to be 0.06 percent, as transmission miles increased by approximately 420 miles.

Transmission miles for each year for non-reporters were calculated by interpolating between UDI reported values obtained from the 2001, 2004, 2007, 2010, 2013 and 2017 UDI directories and 2019 HIFLD data. In cases where a non-reporter previously reported the GHGRP or the Partnership, transmission miles were interpolated between the most recently reported value and the next available UDI value.

Total Industry Emissions

As a final step, total electric power system emissions from 1999 through 2020 were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems), the GHGRP-only reported emissions, and the non-reporting utilities' emissions (determined using the regression equations).

1990 through 2020 Emissions from Manufacture of Electrical Equipment

Three different methods were used to estimate 1990 to 2020 emissions from original electrical equipment manufacturers (OEMs).

- OEM SF_6 emissions from 1990 through 2000 were derived by assuming that manufacturing emissions equaled 10 percent of the quantity of SF_6 provided with new equipment. The 10 percent emission rate is the average of the “ideal” and “realistic” manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O’Connell et al. 2002). The quantity of SF_6 provided with new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000.
- OEM SF_6 emissions from 2000 through 2010 were estimated by (1) interpolating between the emission rate estimated for 2000 (10 percent) and an emission rate estimated for 2011 based on reporting by OEMs through the GHGRP (5.7 percent), and (2) estimating the quantities of SF_6 provided with new equipment for 2001 to 2010. The quantities of SF_6 provided with new equipment were estimated using Partner reported data and the total industry SF_6 nameplate capacity estimate (156.5 MMT CO_2 Eq. in 2010). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2010 was calculated. These ratios were then multiplied by the total industry nameplate capacity estimate for each year to derive the amount of SF_6 provided with new equipment for the entire industry. Additionally, to obtain the 2011 emission rate (necessary for estimating 2001 through 2010 emissions), the estimated 2011 emissions (estimated using the third methodology listed below) were divided by the estimated total quantity of SF_6 provided with new equipment in 2011. The 2011 quantity of SF_6 provided with new equipment was estimated in the same way as the 2001 through 2010 quantities.
- OEM CF_4 emissions from 1991 through 2010 were estimated by using an average ratio of reported SF_6 and CF_4 emissions from 2011 through 2013. This ratio was applied to the estimated SF_6 emissions for 1991 through 2010 to arrive at CF_4 emissions. CF_4 emissions are estimated starting in 1991 and assumed zero prior to 1991 based on the entry of the CF_4/SF_6 gas mixture into the market (Middleton 2000).
- OEM emissions from 2011 through 2020 were estimated using the SF_6 and CF_4 emissions from OEMs reporting to the GHGRP, and an assumption that these reported emissions account for a conservatively low estimate of 50 percent of the total emissions from all U.S. OEMs.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 and CF_4 from Electrical Transmission and Distribution, uncertainties associated with four quantities were estimated: (1) emissions from Partners, (2) emissions from GHGRP-Only Reporters, (3) emissions from Non-Reporters, and (4) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting (through the Partnership or EPA’s GHGRP) and non-reporting Partners. For reporting Partners, individual Partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all Partner-reported data was estimated to be 6.0 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

For GHGRP-Only Reporters, reported SF_6 data was assumed to have an uncertainty of 20 percent.[116] Based on a Monte Carlo analysis, the cumulative uncertainty of all GHGRP-Only reported data was estimated to be 8.5 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2019 from Non-Reporters: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for Non-Reporters. Uncertainties were also estimated regarding (1) estimates of SF_6 and CF_4 emissions from OEMs reporting to EPA's GHGRP, and (2) the assumption on the percent share of OEM emissions from OEMs reporting to EPA's GHGRP.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 4-111. Electrical Transmission and Distribution SF_6 and CF_4 emissions were estimated to be between 3.2 and 4.5 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 18 percent above the emission estimate of 3.8 MMT CO_2 Eq.

Table 4-111: Approach 2 Quantitative Uncertainty Estimates for SF_6 and CF_4 Emissions from Electrical Transmission and Distribution (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to 2018 Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6 and CF_4	3.8	3.2	4.5	-16%	+18%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998 (RAND 2004), and emissions based on atmospheric measurements declined by 17 percent over the same period (Levin et al. 2010).

Several pieces of evidence indicate that U.S. SF_6 emissions were reduced as global emissions were reduced. First, the decreases in sales and emissions coincided with a sharp increase in the price of SF_6 that occurred in the mid-1990s and that affected the United States as well as the rest of the world. A representative from DILO, a major manufacturer of SF_6 recycling equipment, stated that most U.S. utilities began recycling rather than venting SF_6 within two years of the price rise. Finally, the emissions reported by the one U.S. utility that reported its emissions for all the years from 1990 through 1999 under the Partnership showed a downward trend beginning in the mid-1990s.

QA/QC and Verification

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., including a combination of pre-and post-submittal electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent (EPA 2015).[117] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-

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[116] Uncertainty is assumed to be higher for the GHGRP-Only category, because 2011 is the first year that those utilities have reported to EPA.

[117] GHGRP Report Verification Factsheet. See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

submittals checks are consistent with a number of general and category-specific QC procedures including: range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions.

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter and Annex 8 for more details.

Recalculations Discussion

The historical emissions estimated for this source category have undergone the following revisions for the period 1990 through 2019.

- **GHGRP report resubmissions:** Historical estimates for the period 2015 through 2019 were updated relative to the previous report based on revisions to reported historical data in EPA's GHGRP. In addition, EPA identified two facilities that merged with another reporting facility and another facility who reported under one GHGRP ID in 2011 and switched their ID in subsequent years. Estimation methodologies were revised for these four facilities.
- **Transmission mileage update:** Historical estimates for total transmission mileage relied on a growth rate of UDI data from 2012 to 2017 to estimate total transmission mileage for 2019 and 2020. EPA used HIFLD data to replace 2019 data and interpolated transmission mileage between 2016 and 2019 to estimate 2017 and 2018 total transmission mileage.
- **CF_4 emissions from OEMs:** Previous inventories did not capture the emissions of CF_4 from OEMs. EPA used GHGRP data to calculate CF_4 emissions from 2011 through 2019 and used an average ratio of SF_6 emissions to CF_4 emissions in 2011 through 2013 to estimate CF_4 emissions from 1991 through 2010.

As a result of the recalculations, SF_6 emissions from electrical transmission and distribution decreased by 1.20 percent for 2019 relative to the previous report, and SF_6 nameplate capacity decreased by 2.5 percent for 2019 relative to the previous report. On average, SF_6 emission estimates for the entire time series decreased by approximately 0.2 percent per year.

Planned Improvements

EPA plans to more closely examine the methodology used to estimate non-reporter emissions. The current methodology uses a reporter emissions rate to estimate non-reporter emissions. However, the preliminary results of research conducted by the National Oceanic Atmospheric Administration (Hu 2021) indicate that U.S. emissions of SF_6 are significantly higher than what is being estimated in the current inventory for emissions of SF_6 from all sources. Because emissions from non-reporting electric power systems are a significant source of uncertainty in the current U.S. SF_6 inventory, EPA will investigate whether the methodology for determining the emission rate for non-reporters should be revised.

Additionally, as the information on the type of new and retiring equipment is collected through GHGRP reporting, EPA expects this data to provide insight into the relative importance of the two types of equipment as potential emission sources. Historically, hermetically sealed pressure equipment has been considered to be a relatively small source of SF_6 in the United States; however, better estimating its potential source of emissions upon end-of-life (i.e., disposal emissions) is an area for further analysis.

4.26 Nitrous Oxide from Product Uses (CRF Source Category 2G3)

Nitrous oxide (N_2O) is a clear, colorless, oxidizing liquefied gas with a slightly sweet odor which is used in a wide variety of specialized product uses and applications. The amount of N_2O that is actually emitted depends upon the specific product use or application.

There are a total of three N_2O production facilities currently operating in the United States (Ottinger 2021). Nitrous oxide is primarily used in carrier gases with oxygen to administer more potent inhalation anesthetics for general anesthesia, and as an anesthetic in various dental and veterinary applications. The second main use of N_2O is as a propellant in pressure and aerosol products, the largest application being pressure-packaged whipped cream. Small quantities of N_2O also are used in the following applications:

- Oxidizing agent and etchant used in semiconductor manufacturing;
- Oxidizing agent used, with acetylene, in atomic absorption spectrometry;
- Production of sodium azide, which is used to inflate airbags;
- Fuel oxidant in auto racing; and
- Oxidizing agent in blowtorches used by jewelers and others (Heydorn 1997).

Production of N_2O in 2020 was approximately 15 kt (see Table 4-112).

Table 4-112: N_2O Production (kt)

Year	kt
1990	16
2005	15
2016	15
2017	15
2018	15
2019	15
2020	15

Nitrous oxide emissions were 4.2 MMT CO_2 Eq. (14 kt N_2O) in 2020 (see Table 4-113). Production of N_2O stabilized during the 1990s because medical markets had found other substitutes for anesthetics, and more medical procedures were being performed on an outpatient basis using local anesthetics that do not require N_2O. The use of N_2O as a propellant for whipped cream has also stabilized due to the increased popularity of cream products packaged in reusable plastic tubs (Heydorn 1997).

Table 4-113: N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and kt)

Year	MMT CO_2 Eq.	kt
1990	4.2	14
2005	4.2	14
2016	4.2	14
2017	4.2	14
2018	4.2	14
2019	4.2	14
2020	4.2	14

Methodology and Time-Series Consistency

Emissions from N_2O product uses were estimated using the following equation:

Equation 4-25: N_2O Emissions from Product Use

$$E_{pu} = \sum_{a} (P \times S_a \times ER_a)$$

where,

E_{pu} = N_2O emissions from product uses, metric tons
P = Total U.S. production of N_2O, metric tons
a = specific application
S_a = Share of N_2O usage by application *a*
ER_a = Emission rate for application *a*, percent

The share of total quantity of N_2O usage by end-use represents the share of national N_2O produced that is used by the specific subcategory (e.g., anesthesia, food processing). In 2019, the medical/dental industry used an estimated 89.5 percent of total N_2O produced, followed by food processing propellants at 6.5 percent. All other subcategories, including semiconductor manufacturing, atomic absorption spectrometry, sodium azide production, auto racing, and blowtorches, used the remainder of the N_2O produced. This subcategory breakdown has changed only slightly over the past decade. For instance, the small share of N_2O usage in the production of sodium azide declined significantly during the 1990s. Due to the lack of information on the specific time period of the phase-out in this market subcategory, most of the N_2O usage for sodium azide production is assumed to have ceased after 1996, with the majority of its small share of the market assigned to the larger medical/dental consumption subcategory (Heydorn 1997). For 1990 through 1996, N_2O usage was allocated across the following subcategories: medical applications, food processing propellant, and sodium azide production. A usage emissions rate was then applied for each subcategory to estimate the amount of N_2O emitted.

Only the medical/dental and food propellant subcategories were assumed to release emissions into the atmosphere that are not captured under another source category, and therefore these subcategories were the only usage subcategories with emission rates. Emissions of N_2O from semiconductor manufacturing are described in Section 4.23 Electronics Industry (CRF Source Category 2E) and reported under CRF Source Category 2H3. For the medical/dental subcategory, due to the poor solubility of N_2O in blood and other tissues, none of the N_2O is assumed to be metabolized during anesthesia and quickly leaves the body in exhaled breath. Therefore, an emission factor of 100 percent was used for this subcategory (IPCC 2006). For N_2O used as a propellant in pressurized and aerosol food products, none of the N_2O is reacted during the process and all of the N_2O is emitted to the atmosphere, resulting in an emission factor of 100 percent for this subcategory (IPCC 2006). For the remaining subcategories, all of the N_2O is consumed or reacted during the process, and therefore the emission rate was considered to be zero percent (Tupman 2002).

The 1990 through 1992 N_2O production data were obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). Nitrous oxide production data for 1993 through 1995 were not available. Production data for 1996 was specified as a range in two data sources (Heydorn 1997; Tupman 2002). In particular, for 1996, Heydorn (1997) estimates N_2O production to range between 13.6 and 18.1 thousand metric tons. Tupman (2002) provided a narrower range (15.9 to 18.1 thousand metric tons) for 1996 that falls within the production bounds described by Heydorn (1997). Tupman (2002) data are considered more industry-specific and current; therefore, the midpoint of the narrower production range was used to estimate N_2O emissions for years 1993 through 2001 (Tupman 2002). The 2002 and 2003 N_2O production data were obtained from the Compressed Gas Association Nitrous Oxide Fact Sheet and Nitrous Oxide Abuse Hotline (CGA 2002, 2003). These data were also provided as a range. For example, in 2003, CGA (2003) estimates N_2O production to range between 13.6 and 15.9 thousand metric tons. Due to the unavailability of data, production estimates for years 2004 through 2019 were held constant at the 2003 value.

The 1996 share of the total quantity of N_2O used by each subcategory was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997). The 1990 through 1995 share of total quantity of N_2O used by each subcategory was kept the same as the 1996 number provided by SRI Consulting. The 1997 through 2001 share of total quantity of N_2O usage by sector was obtained from communication with a N_2O industry expert (Tupman 2002). The 2002 and 2003 share of total quantity of N_2O usage by sector was obtained from CGA (2002, 2003). Due to the unavailability of data, the share of total quantity of N_2O usage data for years 2004 through 2019 was assumed to equal the 2003 value. The emissions rate for the food processing propellant industry was obtained from SRI Consulting's *Nitrous Oxide, North America* (Heydorn 1997) and confirmed by a N_2O industry expert (Tupman 2002). The emissions rate for all other subcategories was obtained from communication with a N_2O industry expert (Tupman 2002). The emissions rate for the medical/dental subcategory was obtained from the *2006 IPCC Guidelines*.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020.

Uncertainty

The overall uncertainty associated with the 2020 N_2O emission estimate from N_2O product usage was calculated using the *2006 IPCC Guidelines* (2006) Approach 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions include production data, total market share of each end use, and the emission factors applied to each end use, respectively.

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 4-114. Nitrous oxide emissions from N_2O product usage were estimated to be between 3.2 and 5.2 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 24 percent below to 24 percent above the emission estimate of 4.2 MMT CO_2 Eq.

Table 4-114: Approach 2 Quantitative Uncertainty Estimates for N_2O Emissions from N_2O Product Usage (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
N_2O from Product Uses	N_2O	4.2	3.2	5.2	-24%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

For more information on the general QA/QC process applied to this source category, consistent with Volume 1, Chapter 6 of the *2006 IPCC Guidelines*, see the QA/QC and Verification Procedures section in the introduction of the IPPU chapter.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series.

Planned Improvements

EPA recently initiated an evaluation of alternative production statistics for cross-verification and updating time-series activity data, emission factors, assumptions, etc., and a reassessment of N_2O product use subcategories that accurately represent trends. This evaluation includes conducting a literature review of publications and research that may provide additional details on the industry. This work remains ongoing, and thus far no additional sources of data have been found to update this category.

Pending additional resources and planned improvement prioritization, EPA may also evaluate production and use cycles, and the potential need to incorporate a time lag between production and ultimate product use and resulting release of N_2O. Additionally, planned improvements include considering imports and exports of N_2O for product uses.

Finally, for future Inventories, EPA will examine data from EPA's GHGRP to improve the emission estimates for the N_2O product use subcategory. Particular attention will be made to ensure aggregated information can be published without disclosing CBI and time-series consistency, as the facility-level reporting data from EPA's GHGRP are not available for all inventory years as required in this Inventory. This is a lower priority improvement, and EPA is still assessing the possibility of incorporating aggregated GHGRP CBI data to estimate emissions; therefore, this planned improvement is still in development and not incorporated in the current Inventory report.

4.27 Industrial Processes and Product Use Sources of Precursor Gases

In addition to the main greenhouse gases addressed above, many industrial processes can result in emissions of various greenhouse gas precursors. The reporting requirements of the UNFCCC[118] request that information be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but indirectly impact Earth's radiative balance by altering the concentrations of greenhouse gases (e.g., ozone) and atmospheric aerosol (e.g., particulate sulfate). Combustion byproducts such as CO and NO_x are emitted from industrial applications that employ thermal incineration as a control technology. NMVOCs, commonly referred to as "hydrocarbons," are the primary gases emitted from most processes employing organic or petroleum-based products, and can also result from the product storage and handling.

Accidental releases of precursors associated with product use and handling can constitute major emissions in this category. In the United States, emissions from product use are primarily the result of solvent evaporation, whereby the lighter hydrocarbon molecules in the solvents escape into the atmosphere. The major categories of product uses include: degreasing, graphic arts, surface coating, other industrial uses of solvents (e.g., electronics), dry cleaning, and non-industrial uses (e.g., uses of paint thinner). Product usage in the United States also results in the emission of small amounts of hydrofluorocarbons (HFCs) and hydrofluoroethers (HFEs), which are included under Substitution of Ozone Depleting Substances in this chapter.

Total emissions of NO_x, CO, NMVOCs, and SO_2 from non-energy industrial processes and product use from 1990 to 2020 are reported in Table 4-115.

Table 4-115: NO_x, CO, NMVOC, and SO_2 Emissions from Industrial Processes and Product Use (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
NO_x	**592**	**572**	**402**	**397**	**397**	**397**	**397**
Mineral Industry	246	329	221	220	220	220	220
Other Industrial Processes[a]	105	125	80	80	80	80	80
Metal Industry	88	60	61	60	60	60	60
Chemical Industry	152	55	39	37	37	37	37
Product Uses[b]	1	3	1	1	1	1	1

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[118] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

CO	**4,129**		**1,557**		**1,075**	**1,007**	**1,007**	**1,007**	**1,007**
Metal Industry	2,395		752		468	425	425	425	425
Other Industrial Processes[a]	608		420		316	311	311	311	311
Mineral Industry	49		194		179	163	163	163	163
Chemical Industry	1,073		189		110	107	107	107	107
Product Uses[b]	5		2		1	1	1	1	1
NMVOCs	**7,638**		**5,849**		**3,776**	**3,767**	**3,767**	**3,767**	**3,767**
Product Uses[b]	5,216		3,851		2,721	2,696	2,696	2,696	2,696
Other Industrial Processes[a]	1,720		1,708		940	958	958	958	958
Chemical Industry	575		213		69	68	68	68	68
Mineral Industry	16		32		24	24	24	24	24
Metal Industry	111		45		22	20	20	20	20
SO_2	**1,307**		**831**		**466**	**509**	**509**	**509**	**509**
Other Industrial Processes[a]	123		226		186	243	243	243	243
Chemical Industry	269		228		104	101	101	101	101
Mineral Industry	250		215		91	87	87	87	87
Metal Industry	659		158		83	77	77	77	77
Product Uses[b]	6		3		2	1	1	1	1

+ Does not exceed 0.5 kt.

[a] Other Industrial Processes includes storage and transport, other industrial processes (manufacturing of agriculture, food, and kindred products; wood, pulp, paper, and publishing products; rubber and miscellaneous plastic products; machinery products; construction; transportation equipment; and textiles, leather, and apparel products), and miscellaneous sources (catastrophic/accidental release, other combustion (structural fires), health services, repair shops, and fugitive dust). It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.

[b] Product Uses includes the following categories: solvent utilization (degreasing, graphic arts, dry cleaning, surface coating, other industrial, and nonindustrial).

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2021a). For Table 4-115, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs and recategorized from NEI Tier 1/Tier 2 source categories to those more closely aligned with IPCC categories, based on EPA (2022).[119] NEI Tier 1 emission categories related to the IPPU sector categories in this report include: chemical and allied product manufacturing, metals processing, storage and transport, solvent utilization, other industrial processes, and miscellaneous sources. As described in detail in the NEI Technical Support Documentation (TSD) (EPA 2021b), NEI emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological approaches were applied to the entire time series to ensure time-series consistency from 1990 through 2020, which are described in detail in the NEI's TSD and on EPA's Air Pollutant Emission Trends web site (EPA 2021a; EPA 2021b). Updates to historical activity data are documented in NEI's TSD (EPA 2021b). A quantitative uncertainty analysis was not performed.

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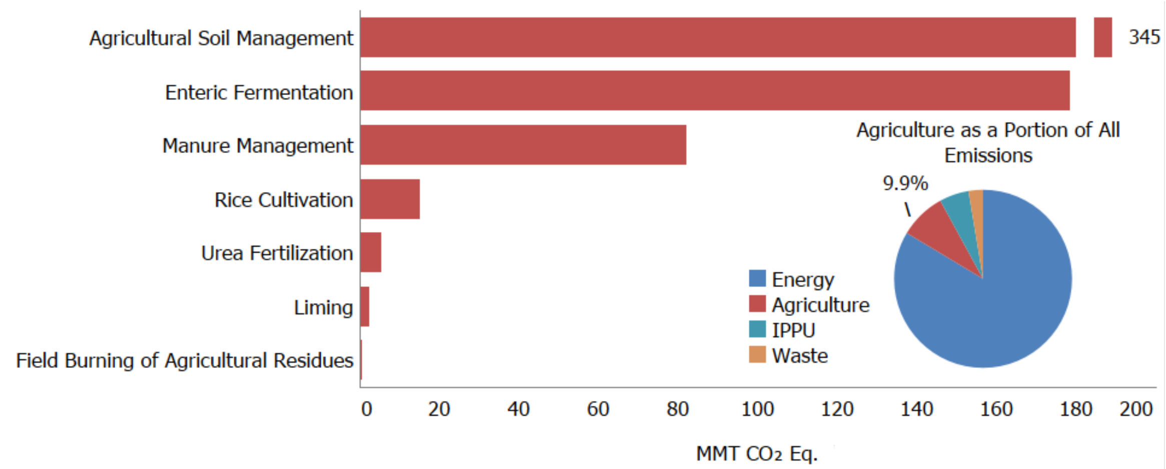
[119] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. Reported NEI emission estimates are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For this report, EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI Tier 1/Tier 2 categories to better align with IPCC source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.6 for more information on this mapping.

5. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of methane (CH_4) from enteric fermentation, livestock manure management, rice cultivation and Field Burning of Agricultural Residues and nitrous oxide (N_2O) emissions from agricultural soil management, livestock manure management, and field burning of agricultural residues; as well as carbon dioxide (CO_2) emissions from liming and urea fertilization (see Figure 5-1). Additional CO_2, CH_4 and N_2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, management on grasslands, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. Carbon dioxide emissions from stationary and mobile on-farm energy use and CH_4 and N_2O emissions from stationary on-farm energy use are reported in the Energy chapter under the Industrial sector emissions. Methane and N_2O emissions from mobile on-farm energy use are reported in the Energy chapter under mobile fossil fuel combustion emissions.

Figure 5-1: 2020 Agriculture Sector Greenhouse Gas Emission Sources



In 2020, the Agriculture sector was responsible for emissions of 594.7 MMT CO_2 Eq.,[1] or 9.9 percent of total U.S. greenhouse gas emissions. Methane emissions from enteric fermentation and manure management represent 26.9 percent and 9.2 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were the largest emitters of CH_4. Emissions of N_2O by agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N_2O emissions, accounting for 74.2 percent. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Manure management and field

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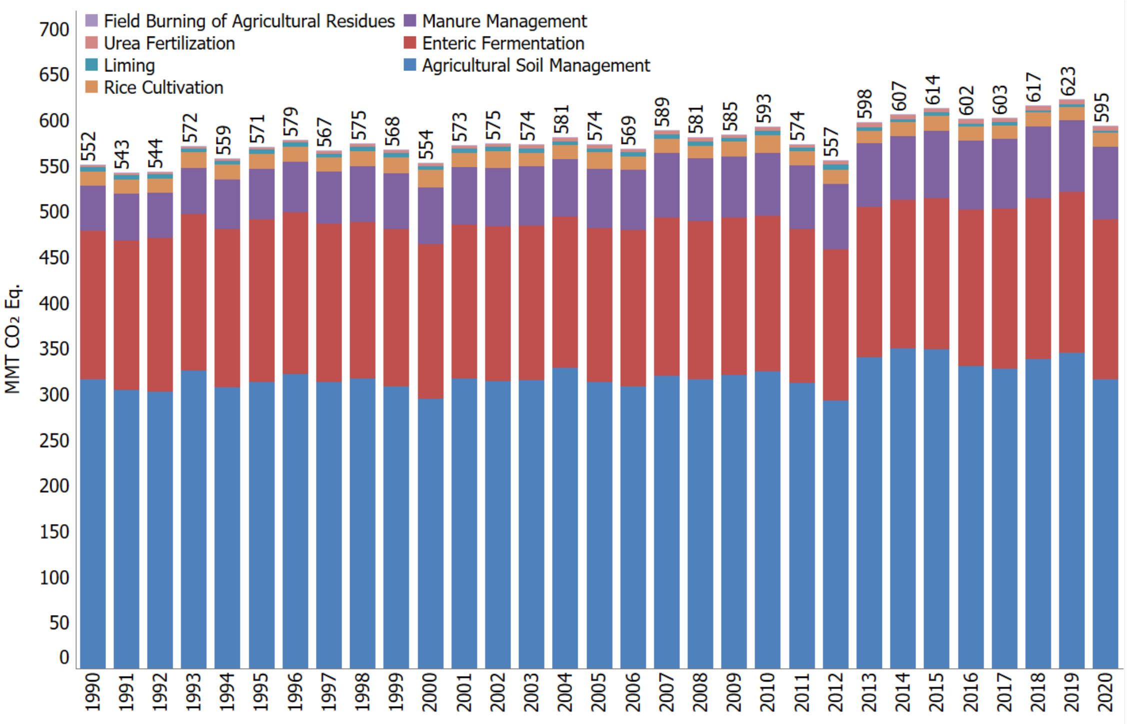
[1] Following the current reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC), this Inventory report presents CO_2 equivalent values based on the *IPCC Fourth Assessment Report* (AR4) GWP values. See the Introduction chapter for more information.

burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming accounted for 0.1 percent and 0.05 percent of total CO_2 emissions from anthropogenic activities, respectively.

Table 5-1 and Table 5-2 present emission estimates for the Agriculture sector. Between 1990 and 2020, CO_2 and CH_4 emissions from agricultural activities increased by 8.1 percent and 16.9 percent, respectively, while N_2O emissions from agricultural activities fluctuated from year to year, but increased by 1.8 percent overall. Trends in sources of agricultural emissions over the 1990 to 2020 time series are shown in Figure 5-2.

Figure 5-2: Trends in Agriculture Sector Greenhouse Gas Emission Sources



Each year, some emission estimates in the Agriculture sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 through 2019) to ensure that the trend is accurate. This year's notable updates include (1) Enteric Fermentation: updated to use Cattle Enteric Fermentation Model (CEFM) for all years; (2) Manure Management: Updated animal population data, updated state animal population distribution methodology, updated animal population data, and updated MCF for pastures to align with IPCC 2019 guidance; (3) Urea Fertilization: Updates to fertilizer consumption data and calculation formula; (4) Liming: using recently acquired limestone and dolomite data. In total, the improvements made to the Agriculture sector in this Inventory decreased greenhouse gas emissions by 5.8 MMT CO_2 Eq. (0.9 percent) in 2019. For more information on specific methodological updates, please see the Recalculations discussions within the respective source category sections of this chapter.

Emissions reported in the Agriculture chapter include those from all states; however, for Hawaii and Alaska some agricultural practices that can increase nitrogen availability in the soil, and thus cause N_2O emissions, are not included (see chapter sections on "Uncertainty and Time-Series Consistency" and "Planned Improvements" for more details). In addition, U.S. Territories and the District of Columbia are not estimated due to incomplete data, with the exception of Urea Fertilization in Puerto Rico. EPA continues to identify and review available data on an ongoing basis to include agriculture emissions from territories, to the extent they are occurring, in future Inventories. Other minor outlying U.S. territories in the Pacific Islands have no permanent populations (e.g., Baker Island) and therefore EPA assumes no agriculture activities are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this Inventory.

Table 5-1: Emissions from Agriculture (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**7.1**	**7.9**	**7.8**	**8.0**	**7.3**	**7.6**	**7.7**
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3
Liming	4.7	4.3	3.1	3.1	2.2	2.4	2.4
CH_4	**214.7**	**235.5**	**244.7**	**247.8**	**251.1**	**250.3**	**250.9**
Enteric Fermentation	163.5	168.0	171.3	174.9	175.7	176.1	175.2
Manure Management	34.8	49.0	57.1	57.5	59.4	58.7	59.6
Rice Cultivation	16.0	18.0	15.8	14.9	15.6	15.1	15.7
Field Burning of Agricultural Residues	0.4	0.4	0.4	0.4	0.4	0.4	0.4
N_2O	**330.1**	**330.3**	**349.4**	**347.5**	**358.4**	**365.0**	**336.1**
Agricultural Soil Management	316.0	313.8	330.8	328.3	338.9	345.3	316.2
Manure Management	13.9	16.3	18.4	19.0	19.3	19.5	19.7
Field Burning of Agricultural Residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Total	**551.9**	**573.6**	**601.9**	**603.2**	**616.7**	**622.9**	**594.7**

Note: Totals may not sum due to independent rounding.

Table 5-2: Emissions from Agriculture (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CO_2	**7,084**	**7,854**	**7,761**	**7,977**	**7,267**	**7,553**	**7,657**
Urea Fertilization	2,417	3,504	4,679	4,897	5,019	5,140	5,275
Liming	4,667	4,349	3,081	3,080	2,248	2,413	2,382
CH_4	**8,587**	**9,419**	**9,787**	**9,911**	**10,043**	**10,013**	**10,036**
Enteric Fermentation	6,539	6,722	6,853	6,998	7,028	7,046	7,007
Manure Management	1,394	1,960	2,285	2,300	2,375	2,348	2,383
Rice Cultivation	640	720	631	596	623	602	630
Field Burning of Agricultural Residues	15	17	17	17	17	17	17
N_2O	**1,108**	**1,108**	**1,173**	**1,166**	**1,203**	**1,225**	**1,128**
Agricultural Soil Management	1,060	1,053	1,110	1,102	1,137	1,159	1,061
Manure Management	47	55	62	64	65	65	66
Field Burning of Agricultural Residues	1	1	1	1	1	1	1

Note: Totals may not sum due to independent rounding.

Box 5-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter, are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions provided in the Agriculture chapter do not preclude alternative examinations, but rather, this chapter presents emissions in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions from agricultural activities.

5.1 Enteric Fermentation (CRF Source Category 3A)

Methane is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a byproduct, which can be exhaled or eructated by the animal. The amount of CH_4 produced and emitted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.[2]

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions per unit of body mass among all animal types.

Non-ruminant animals (e.g., swine, horses, and mules and asses) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal-mass basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality and/or higher feed intake leads to higher CH_4 emissions. Feed intake is positively correlated to animal size, growth rate, level of activity and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types (e.g., animals in feedlots or grazing on pasture).

Methane emission estimates from enteric fermentation are provided in Table 5-3 and Table 5-4. Total livestock CH_4 emissions in 2020 were 175.2 MMT CO_2 Eq. (7,007 kt). Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 72 percent in 2020. Emissions from dairy cattle in 2020 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, goats, American bison, mules and asses.[3]

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[2] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[3] Enteric fermentation emissions from poultry are not estimated because no IPCC method has been developed for determining enteric fermentation CH_4 emissions from poultry; at this time, developing of a country-specific method would require a disproportionate amount of resources given the small magnitude of this source category. Enteric fermentation emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

Table 5-3: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	2005	2016	2017	2018	2019	2020
Beef Cattle	118.5	124.7	122.6	125.8	126.0	126.5	125.3
Dairy Cattle	38.7	36.8	42.5	42.9	43.4	43.3	43.6
Swine	2.0	2.3	2.6	2.7	2.8	2.9	2.9
Horses	1.0	1.7	1.4	1.3	1.2	1.1	1.1
Sheep	2.6	1.4	1.2	1.2	1.2	1.2	1.2
Goats	0.6	0.7	0.6	0.6	0.6	0.6	0.6
American Bison	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Mules and Asses	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**163.5**	**168.0**	**171.3**	**174.9**	**175.7**	**176.1**	**175.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-4: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	2005	2016	2017	2018	2019	2020
Beef Cattle	4,742	4,986	4,905	5,033	5,042	5,062	5,013
Dairy Cattle	1,547	1,473	1,700	1,715	1,737	1,732	1,744
Swine	81	92	105	108	110	115	116
Horses	40	70	54	51	48	46	43
Sheep	102	55	48	47	47	47	47
Goats	23	26	24	24	24	25	25
American Bison	4	17	15	15	15	16	16
Mules and Asses	1	2	3	3	3	3	3
Total	**6,539**	**6,722**	**6,853**	**6,998**	**7,028**	**7,046**	**7,007**

Note: Totals may not sum due to independent rounding.

From 1990 to 2020, emissions from enteric fermentation have increased by 7.2 percent. From 2019 to 2020, emissions decreased by 0.5 percent, largely driven by a decrease in cattle populations. While emissions generally follow trends in cattle populations, over the long term there are exceptions. For example, while dairy cattle emissions increased 12.7 percent over the entire time series, the population has declined by 3.6 percent, and milk production increased 46 percent (USDA 2021a). These trends indicate that while emissions per head are increasing, emissions per unit of product (i.e., meat, milk) are decreasing.

Generally, from 1990 to 1995 emissions from beef cattle increased and then decreased from 1996 to 2004. These trends were mainly due to fluctuations in beef cattle populations and increased digestibility of feed for feedlot cattle. Beef cattle emissions generally increased from 2004 to 2007, as beef cattle populations increased, and an extensive literature review indicated a trend toward a decrease in feed digestibility for those years. Beef cattle emissions decreased again from 2007 to 2014, as populations again decreased, but increased from 2015 to 2019, consistent with another increase in population over those same years. Emissions and populations slightly declined in 2020.

Emissions from dairy cattle generally trended downward from 1990 to 2004, along with an overall dairy cattle population decline during the same period. Similar to beef cattle, dairy cattle emissions rose from 2004 to 2007 due to population increases and a decrease in feed digestibility (based on an analysis of more than 350 dairy cow diets used by producers across the United States). Dairy cattle emissions have continued to trend upward since 2007, generally in line with dairy cattle population changes.

Regarding trends in other animals, populations of sheep have steadily declined, with an overall decrease of 54 percent since 1990. Horse populations are 8 percent greater than they were in 1990, but their numbers have been declining by an average of 4 percent annually since 2007. Goat populations increased by about 20 percent through 2007, steadily decreased through 2012, then increased again, by about 1 percent annually, through 2020. Swine populations have trended upward through most of the time series, increasing 43 percent from 1990 to 2020. The population of American bison more than quadrupled over the 1990 to 2020 time period, while the population of mules and asses increased by a factor of five.

Methodology and Time-Series Consistency

Livestock enteric fermentation emission estimate methodologies fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of enteric fermentation CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle. Emission estimates for other domesticated animals (horses, sheep, swine, goats, American bison, and mules and asses) were estimated using the IPCC Tier 1 approach, as suggested by the *2006 IPCC Guidelines* (see the Planned Improvements section).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach. The Cattle Enteric Fermentation Model (CEFM), developed by EPA and used to estimate cattle CH_4 emissions from enteric fermentation using IPCC's Tier 2 method, incorporates this information and other analyses of livestock population, feeding practices, and production characteristics.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2020. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation. In addition, variables and the resulting emissions are also available at the state level in Annex 3.10.

Inventory Methodology for Cattle

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
    - Calves
    - Heifer Replacements
    - Cows
- Beef Cattle
    - Calves
    - Heifer Replacements
    - Heifer and Steer Stockers
    - Animals in Feedlots (Heifers and Steer)
    - Cows
    - Bulls

Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.10. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS) *QuickStats* database (USDA 2021a).

Diet characteristics were estimated by region for dairy, grazing beef, and feedlot beef cattle. These diet characteristics were used to calculate digestible energy (DE) values (expressed as the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m) (expressed as the fraction of gross energy converted to CH_4) for each regional population category. The IPCC recommends Y_m ranges of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for other well-fed cattle consuming temperate-climate feed types (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies and scientific literature, expert opinion, and modeling of animal physiology.

The diet characteristics for dairy cattle were based on Donovan (1999) and an extensive review of nearly 20 years of literature from 1990 through 2009. Estimates of DE were national averages based on the feed components of the diets observed in the literature for the following year groupings: 1990 through 1993, 1994 through 1998, 1999 through 2003, 2004 through 2006, 2007, and 2008 onward.[4] Base year Y_m values by region were estimated using Donovan (1999). As described in ERG (2016), a ruminant digestion model (COWPOLL, as selected in Kebreab et al. 2008) was used to evaluate Y_m for each diet evaluated from the literature, and a function was developed to adjust regional values over time based on the national trend. Dairy replacement heifer diet assumptions were based on the observed relationship in the literature between dairy cow and dairy heifer diet characteristics.

For feedlot animals, the DE and Y_m values used for 1990 were recommended by Johnson (1999). Values for DE and Y_m for 1991 through 1999 were linearly extrapolated based on the 1990 and 2000 data. DE and Y_m values for 2000 onwards were based on survey data in Galyean and Gleghorn (2001) and Vasconcelos and Galyean (2007).

For grazing beef cattle, Y_m values were based on Johnson (2002), DE values for 1990 through 2006 were based on specific diet components estimated from Donovan (1999), and DE values from 2007 onwards were developed from an analysis by Archibeque (2011), based on diet information in Preston (2010) and USDA-APHIS:VS (2010). Weight and weight gains for cattle were estimated from Holstein (2010), Doren et al. (1989), Enns (2008), Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000), and expert opinion. See Annex 3.10 for more details on the method used to characterize cattle diets and weights in the United States.

Calves younger than 4 months are not included in emission estimates because calves consume mainly milk and the IPCC recommends the use of a Y_m of zero for all juveniles consuming only milk. Diets for calves aged 4 to 6 months are assumed to go through a gradual weaning from milk decreasing to 75 percent at 4 months, 50 percent at age 5 months, and 25 percent at age 6 months. The portion of the diet made up with milk still results in zero emissions. For the remainder of the diet, beef calf DE and Y_m are set equivalent to those of beef replacement heifers, while dairy calf DE is set equal to that of dairy replacement heifers and dairy calf Y_m is provided at 4 and 7 months of age by Soliva (2006). Estimates of Y_m for 5 and 6 month old dairy calves are linearly interpolated from the values provided for 4 and 7 months.

To estimate CH_4 emissions, the population was divided into state, age, sub-type (i.e., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, heifers and steers in feedlots, bulls, beef calves 4 to 6 months, and dairy calves 4 to 6 months), and production (i.e., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. The transition matrix was used to simulate the age and weight structure of each sub-type on a monthly basis in order to more accurately reflect the fluctuations that occur throughout the year. Cattle diet characteristics were then used in conjunction with Tier 2 equations from IPCC (2006) to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, heifer feedlot animals, bulls, and calves. To estimate emissions from cattle, monthly population data from the transition matrix were multiplied by the calculated emission factor for each cattle type. More details are provided in Annex 3.10.

Non-Cattle Livestock

Emission estimates for other animal types were based on average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type. Methane emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2020. Additionally, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle.

Annual livestock population data for 1990 to 2020 for sheep; swine; goats; horses; mules and asses; and American bison were obtained for available years from USDA-NASS (USDA 2021a; USDA 2019). Horse, goat, and mule and ass

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[4] Due to inconsistencies in the 2003 literature values, the 2002 values were used for 2003 as well.

population data were available for 1987, 1992, 1997, 2002, 2007, 2012, and 2017 (USDA 2019); the remaining years between 1990 and 2020 were interpolated and extrapolated from the available estimates (with the exception of goat populations being held constant between 1990 and 1992). American bison population estimates were available from USDA for 2002, 2007, 2012, and 2017 (USDA 2019) and from the National Bison Association (1999) for 1990 through 1999. Additional years were based on observed trends from the National Bison Association (1999), interpolation between known data points, and extrapolation beyond 2012, as described in more detail in Annex 3.10.

Methane emissions from sheep, goats, swine, horses, American bison, and mules and asses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC 2006). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. For American bison, the emission factor for buffalo was used and adjusted based on the ratio of live weights to the 0.75 power. The methodology is the same as that recommended by IPCC (2006).

Uncertainty

A quantitative uncertainty analysis for this source category was performed using the IPCC-recommended Approach 2 uncertainty estimation methodology based on a Monte Carlo Stochastic Simulation technique as described in ICF (2003). These uncertainty estimates were developed for the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC). While there are plans to update the uncertainty to reflect recent methodological updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2020 emission estimates in this Inventory.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for the uncertainty analysis. A normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run) to ensure only positive values would be simulated. For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources; others were based on expert opinion and best estimates. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed through expert judgment.

Among the individual cattle sub-source categories, beef cattle account for the largest amount of CH_4 emissions, as well as the largest degree of uncertainty in the emission estimates—due mainly to the difficulty in estimating the diet characteristics for grazing members of this animal group. Among non-cattle, horses represent the largest percent of uncertainty in the previous uncertainty analysis because the Food and Agricultural Organization of the United Nations (FAO) population estimates used for horses at that time had a higher degree of uncertainty than for the USDA population estimates used for swine, goats, and sheep. The horse populations are now from the same USDA source as the other animal types, and therefore the uncertainty range around horses is likely overestimated. Cattle calves, American bison, mules and asses were excluded from the initial uncertainty estimate because they were not included in emission estimates at that time.

The uncertainty ranges associated with the activity data-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis are summarized in Table 5-5. Based on this analysis, enteric fermentation CH_4 emissions in 2020 were estimated to be between 155.9 and 206.7 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 11 percent below to 18 percent above the 2020 emission estimate of 175.2 MMT CO_2 Eq.

Table 5-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b, c] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	175.2	155.9	206.7	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates from the 2003 submission and applied to the 2020 estimates.

[c] The overall uncertainty calculated in 2003, and applied to the 2020 emission estimate, did not include uncertainty estimates for calves, American bison, and mules and asses. Additionally, for bulls the emissions estimate was based on the Tier 1 methodology. Since bull emissions are now estimated using the Tier 2 method, the uncertainty surrounding their estimates is likely lower than indicated by the previous uncertainty analysis.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the General (IPCC Tier 1) and category-specific (Tier 2) Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Category-specific or Tier 2 QA procedures included independent review of emission estimate methodologies from previous inventories.

As part of the quality assurance process, average implied emissions factors for U.S. dairy and beef cattle were developed based on CEFM output and compared to emission factors for other countries provided by IPCC (2006). This comparison is discussed in further detail in Annex 3.10.

Over the past few years, particular importance has been placed on harmonizing the data exchange between the enteric fermentation and manure management source categories. The current Inventory now utilizes the transition matrix from the CEFM for estimating cattle populations and weights for both source categories, and the CEFM is used to output volatile solids and nitrogen excretion estimates using the diet assumptions in the model in conjunction with the energy balance equations from the IPCC (2006). This approach facilitates the QA/QC process for both of these source categories.

Recalculations Discussion

In the previous Inventory, 1990 to 2017 estimates were retained from the 1990 through 2017 Inventory, and 2018 and 2019 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current Inventory, the CEFM was used for cattle for all years, resulting in different estimates for 2018 and 2019 than the prior Inventory. For non-cattle livestock in the current Inventory, updated Tier 1 estimates were calculated for 2018 and 2019, yielding different results than the simplified approach used for these years in the prior Inventory.

For cattle, there were also changes to emissions resulting from activity data changes, including:

- The USDA published minor data revisions that EPA incorporated into the CEFM:
  - Calf birth data were revised for 2013, 2016, and 2017;
  - Dairy cow milk production values were updated for several states for 2013 through 2017;
  - Cattle populations were revised for various states, depending on the year and cattle type, from 2014 through 2017;
  - Cattle on feed population data were updated for 2014 through 2017;

    - Slaughter data were revised for 2017.

- EPA updated average milk fat in the CEFM from a constant IPCC default value of 4 percent to annual average values of monthly milk fat values from USDA's Economic Research Services dairy data (USDA 2021b). These values ranged from 3.7 percent to 4.1 percent across the time series and are more representative of U.S. livestock industry.

"Other" (non-cattle) livestock emissions were impacted by the following changes made between the current and prior Inventories:

- USDA published updated animal population data that impacted 2018 emissions for poultry, sheep, and swine.
- The manure management inventory updated how "other" state USDA combined populations were distributed to their respective states (ERG 2021). See Section 5.2. These changes impacted emissions for 1990 through 2019 for both sheep and poultry, as well as 2010 through 2016 for swine.

All of these recalculations impacted the overall emission estimates between 0.5 and 1.4 percent over the time series.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. EPA conducts the following list of regular annual assessments of data availability when updating the estimates to extend time series each year:

- Further research to improve the estimation of dry matter intake (as gross energy intake) using data from appropriate production systems;
- Updating input variables that are from older data sources, such as beef births by month, beef and dairy annual calving rates, and beef cow lactation rates;
- Investigating the availability of data for dairy births by month, to replace the current assumption that births are evenly distributed throughout the year;
- Investigating the availability of annual data for the DE, Y_m, and crude protein values of specific diet and feed components for grazing and feedlot animals;
- Further investigation on additional sources or methodologies for estimating DE for dairy cattle, given the many challenges in characterizing dairy cattle diets;
- Further evaluation of the assumptions about weights and weight gains for beef cows, such that trends beyond 2007 are updated, rather than held constant; and
- Further evaluation of the estimated weight for dairy cows (i.e., 1,500 lbs) that is based solely on Holstein cows as mature dairy cow weight is likely slightly overestimated, based on knowledge of the breeds of dairy cows in the United States.

Depending upon the outcome of ongoing investigations, future improvement efforts for enteric fermentation could include some of the following options which are additional to the regular updates, and may or may not have implications for regular updates once addressed:

- Potentially updating to a Tier 2 methodology for other animal types (i.e., sheep, swine, goats, horses); efforts to move to Tier 2 will consider the emissions significance of livestock types;
- Investigation of methodologies and emission factors for including enteric fermentation emission estimates from poultry;
- Comparison of the current CEFM with other models that estimate enteric fermentation emissions for quality assurance and verification;

- Investigation of recent research implications suggesting that certain parameters in enteric models may be simplified without significantly diminishing model accuracy; and
- Recent changes that have been implemented to the CEFM warrant an assessment of the current uncertainty analysis; therefore, a revision of the quantitative uncertainty surrounding emission estimates from this source category will be initiated. EPA plans to perform this uncertainty analysis following the completed updates to the CEFM.

EPA is continuously investigating these recommendations and potential improvements and working with USDA and other experts to utilize the best available data and methods for estimating emissions. Many of these improvements are major updates and may take multiple years to implement in full.

5.2 Manure Management (CRF Source Category 3B)

The treatment, storage, and transportation of livestock manure can produce anthropogenic CH_4 and N_2O emissions.[5] Methane is produced by the anaerobic decomposition of manure and nitrous oxide is produced from direct and indirect pathways through the processes of nitrification and denitrification; in addition, there are many underlying factors that can affect these resulting emissions from manure management, as described below.

When livestock manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of the volatile solids component in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce CO_2 and little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and animal type (particularly the different animal digestive systems), also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

As previously stated, N_2O emissions are produced through both direct and indirect pathways. Direct N_2O emissions are produced as part of the nitrogen (N) cycle through the nitrification and denitrification of the N in livestock dung and urine.[6] There are two pathways for indirect N_2O emissions. The first is the result of the volatilization of N in manure (as NH_3 and NO_x) and the subsequent deposition of these gases and their products (NH_4^+ and NO_3^-) onto soils and the surface of lakes and other waters. The second pathway is the runoff and leaching of N from manure into the groundwater below, into riparian zones receiving drain or runoff water, or into the ditches, streams, rivers, and estuaries into which the land drainage water eventually flows.

The production of direct N_2O emissions from livestock manure depends on the composition of the manure (manure includes both feces and urine), the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For direct N_2O emissions to occur, the manure must first be handled aerobically where organic N is mineralized or decomposed to NH_4 which is then nitrified to NO_3 (producing some N_2O as a

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[5] CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2 (IPCC 2006).

[6] Direct and indirect N_2O emissions from dung and urine spread onto fields either directly as daily spread or after it is removed from manure management systems (i.e., lagoon, pit, etc.) and from livestock dung and urine deposited on pasture, range, or paddock lands are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector.

byproduct) (nitrification). Next, the manure must be handled anaerobically where the nitrate is then denitrified to N_2O and N_2 (denitrification). NO_x can also be produced during denitrification (Groffman et al. 2000; Robertson and Groffman 2015). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total N excreted is expected to convert to N_2O in the waste management system (WMS).

Indirect N_2O emissions are produced when nitrogen is lost from the system through volatilization (as NH_3 or NO_x) or through runoff and leaching. The vast majority of volatilization losses from these operations are NH_3. Although there are also some small losses of NO_x, there are no quantified estimates available for use, so losses due to volatilization are only based on NH_3 loss factors. Runoff losses would be expected from operations that house animals or store manure in a manner that is exposed to weather. Runoff losses are also specific to the type of animal housed on the operation due to differences in manure characteristics. Little information is known about leaching from manure management systems as most research focuses on leaching from land application systems. Since leaching losses are expected to be minimal, leaching losses are coupled with runoff losses and the runoff/leaching estimate provided in this chapter does not account for any leaching losses.

Estimates of CH_4 emissions from manure management in 2020 were 59.6 MMT CO_2 Eq. (2,383 kt); in 1990, emissions were 34.8 MMT CO_2 Eq. (1,394 kt). This represents a 71 percent increase in emissions from 1990. Emissions increased on average by 0.8 MMT CO_2 Eq. (2 percent) annually over this period. The majority of this increase is due to swine and dairy cow manure, where emissions increased 44 and 122 percent, respectively. From 2019 to 2020, there was a 1 percent increase in total CH_4 emissions from manure management, mainly due to an increase in swine populations as well as an update to milk fat content which increased the average volatile solids excretion for dairy cows.

Although a large quantity of managed manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy cattle and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations controlling the application of manure nutrients to land have shifted manure management practices at smaller dairies from daily spread systems to storage and management of the manure on site. In many cases, manure management systems with the most substantial methane emissions are those associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system (IPCC 2006).

While national dairy animal populations have decreased since 1990, some states have seen increases in their dairy cattle populations as the industry becomes more concentrated in certain areas of the country and the number of animals contained on each facility increases. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus, the shift toward larger dairy cattle and swine facilities since 1990 has translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This significant shift in both the dairy cattle and swine industries was accounted for by incorporating state and WMS-specific CH_4 conversion factor (MCF) values in combination with the 1992, 1997, 2002, 2007, 2012, and 2017 farm-size distribution data reported in the U.S. Department of Agriculture (USDA) *Census of Agriculture* (USDA 2019d).

In 2020, total N_2O emissions from manure management were estimated to be 19.7 MMT CO_2 Eq. (66 kt); in 1990, emissions were 13.9 MMT CO_2 Eq. (47 kt). These values include both direct and indirect N_2O emissions from manure management. Nitrous oxide emissions have increased since 1990. Small changes in N_2O emissions from individual animal groups exhibit the same trends as the animal group populations, with the overall net effect that N_2O emissions showed a 41 percent increase from 1990 to 2020 and a 0.9 percent increase from 2019 to 2020. Overall shifts toward liquid systems have driven down the emissions per unit of nitrogen excreted as dry manure handling systems have greater aerobic conditions that promote N_2O emissions.

Table 5-6 and Table 5-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.[7]

Table 5-6: CH_4 and N_2O Emissions from Manure Management (MMT CO_2 Eq.)

Gas/Animal Type	1990	2005	2016	2017	2018	2019	2020
CH_4[a]	**34.8**	**49.0**	**57.1**	**57.5**	**59.4**	**58.7**	**59.6**
Dairy Cattle	14.3	23.6	30.8	31.2	32.0	30.9	31.7
Swine	15.5	20.3	21.1	21.0	22.0	22.3	22.4
Poultry	3.3	3.2	3.3	3.4	3.5	3.6	3.5
Beef Cattle	1.6	1.7	1.7	1.7	1.8	1.8	1.8
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sheep	0.1	0.1	+	+	+	+	+
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
N_2O[b]	**13.9**	**16.3**	**18.4**	**19.0**	**19.3**	**19.5**	**19.7**
Beef Cattle	5.9	7.2	8.5	8.9	9.1	9.2	9.4
Dairy Cattle	5.2	5.4	6.0	6.1	6.1	6.1	6.1
Swine	1.2	1.6	1.9	2.0	2.0	2.1	2.1
Poultry	1.4	1.6	1.6	1.6	1.7	1.7	1.7
Sheep	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Horses	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA
Total	**48.8**	**65.3**	**75.5**	**76.5**	**78.7**	**78.2**	**79.2**

+ Does not exceed 0.05 MMT CO_2 Eq.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the Agricultural Soils Management sector. Totals may not sum due to independent rounding.

Table 5-7: CH_4 and N_2O Emissions from Manure Management (kt)

Gas/Animal Type	1990	2005	2016	2017	2018	2019	2020
CH_4[a]	**1,394**	**1,960**	**2,285**	**2,300**	**2,375**	**2,348**	**2,383**
Dairy Cattle	572	943	1,232	1,248	1,278	1,237	1,269
Swine	621	812	846	840	882	891	895
Poultry	131	130	134	136	139	144	142
Beef Cattle	63	67	68	70	70	71	71
Horses	4	5	3	3	3	3	3
Sheep	3	2	2	2	2	2	2
Goats	+	+	+	+	+	+	+
American Bison	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+0 0	+	+

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[7] Manure management emissions from camels are not estimated because there is no significant population of camels in the United States. Given the insignificance of estimated camel emissions in terms of the overall level and trend in national emissions, there are no immediate improvement plans to include this emissions category in the Inventory. See Annex 5 for more information on significance of estimated camel emissions.

N_2O^b	**47**	**55**	**62**	**64**	**65**	**65**	**66**
Beef Cattle	20	24	28	30	30	31	31
Dairy Cattle	17	18	20	20	21	20	21
Swine	4	5	6	7	7	7	7
Poultry	5	5	5	5	6	6	6
Sheep	+	1	1	1	1	1	1
Horses	+	+	+	+	+	+	+
Goats	+	+	+	+	+	+	+
Mules and Asses	+	+	+	+	+	+	+
American Bison[c]	NA	NA	NA	NA	NA	NA	NA

+ Does not exceed 0.5 kt.

NA (Not Available)

[a] Accounts for CH_4 reductions due to capture and destruction of CH_4 at facilities using anaerobic digesters.

[b] Includes both direct and indirect N_2O emissions.

[c] There are no American bison N_2O emissions from managed systems; American bison are maintained entirely on pasture, range, and paddock.

Notes: N_2O emissions from manure deposited on pasture, range and paddock are included in the Agricultural Soils Management sector. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM previously described for Enteric Fermentation. These methodologies use:

- IPCC (2006; 2019) Tier 1 default N_2O emission factors and MCFs for dry systems
- U.S. specific MCFs for liquid systems (ERG 2001)
- U.S. specific values for volatile solids (VS) production rate and nitrogen excretion rate for some animal types, including cattle values from the CEFM

This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types. This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management.

See Annex 3.11 for more detailed information on the methodology (including detailed formulas and emission factors), data used to calculate CH_4 and N_2O emissions, and emission results (including input variables and results at the state-level) from manure management.

Methane Calculation Methods

The following inputs were used in the calculation of manure management CH_4 emissions for 1990 through 2020:

- Animal population data (by animal type and state);
- Typical animal mass (TAM) data (by animal type);
- Portion of manure managed in each WMS, by state and animal type;
- VS production rate (by animal type and state or United States);
- Methane producing potential (B_0) of the volatile solids (by animal type); and
- Methane conversion factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by state and manure management system, including the impacts of any biogas collection efforts).

Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources are described below:

- Annual animal population data for 1990 through 2020 for all livestock types, except goats, horses, mules and asses, and American bison were obtained from the USDA-NASS. For cattle, the USDA populations were utilized in conjunction with birth rates, detailed feedlot placement information, and slaughter weight data to create the transition matrix in the Cattle Enteric Fermentation Model (CEFM) that models cohorts of individual animal types and their specific emission profiles. The key variables tracked for each of the cattle population categories are described in Section 5.1 and in more detail in Annex 3.10. Goat population data for 1992, 1997, 2002, 2007, 2012, and 2017; horse and mule and ass population data for 1987, 1992, 1997, 2002, 2007, 2012, and 2017; and American bison population for 2002, 2007, 2012, and 2017 were obtained from the *Census of Agriculture* (USDA 2019d). American bison population data for 1990 through 1999 were obtained from the National Bison Association (1999).

- The TAM is an annual average weight that was obtained for animal types other than cattle from information in USDA's *Agricultural Waste Management Field Handbook* (USDA 1996), the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and others (Meagher 1986; EPA 1992; Safley 2000; ERG 2003b; IPCC 2006; ERG 2010a). For a description of the TAM used for cattle, see Annex 3.10.
- WMS usage was estimated for swine and dairy cattle for different farm size categories using state and regional data from USDA (USDA APHIS 1996; Bush 1998; Ott 2000; USDA 2016c) and EPA (ERG 2000a; EPA 2002a and 2002b; ERG 2018, ERG 2019). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a; USDA APHIS 2000; UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992). American bison WMS usage was assumed to be the same as not on feed (NOF) cattle, while mules and asses were assumed to be the same as horses.
- VS production rates for all cattle except for calves were calculated by head for each state and animal type in the CEFM. VS production rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data that was not available in the most recent *Handbook* were obtained from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the *2006 IPCC Guidelines* (IPCC 2006). American bison VS production was assumed to be the same as NOF bulls.
- B_0 was determined for each animal type based on literature values (Morris 1976; Bryant et al. 1976; Hashimoto 1981; Hashimoto 1984; EPA 1992; Hill 1982; Hill 1984).
- MCFs for dry systems were set equal to default IPCC factors based on state climate for each year (IPCC 2006; IPCC 2019). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation which is consistent with IPCC (2006) Tier 2 methodology.
- Data from anaerobic digestion systems with CH_4 capture and combustion were obtained from the EPA AgSTAR Program, including information available in the AgSTAR project database (EPA 2021). Anaerobic digester emissions were calculated based on estimated methane production and collection and destruction efficiency assumptions (ERG 2008).
- For all cattle except for calves, the estimated amount of VS (kg per animal-year) managed in each WMS for each animal type, state, and year were taken from the CEFM, assuming American bison VS production to be the same as NOF bulls. For animals other than cattle, the annual amount of VS (kg per year) from manure excreted in each WMS was calculated for each animal type, state, and year. This calculation multiplied the animal population (head) by the VS excretion rate (kg VS per 1,000 kg animal mass per day), the TAM (kg animal mass per head) divided by 1,000, the WMS distribution (percent), and the number of days per year (365.25).

The estimated amount of VS managed in each WMS was used to estimate the CH_4 emissions (kg CH_4 per year) from each WMS. The amount of VS (kg per year) were multiplied by the B_0 (m^3 CH_4 per kg VS), the MCF for that WMS (percent), and the density of CH_4 (kg CH_4 per m^3 CH_4). The CH_4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH_4 emissions. See details in Step 5 of Annex 3.11.

Nitrous Oxide Calculation Methods

The following inputs were used in the calculation of direct and indirect manure management N_2O emissions for 1990 through 2020:

- Animal population data (by animal type and state);
- TAM data (by animal type);
- Portion of manure managed in each WMS (by state and animal type);
- Total Kjeldahl N excretion rate (Nex);
- Direct N_2O emission factor (EF_{WMS});
- Indirect N_2O emission factor for volatilization ($EF_{volatilization}$);
- Indirect N_2O emission factor for runoff and leaching ($EF_{runoff/leach}$);
- Fraction of N loss from volatilization of NH_3 and NO_x ($Frac_{gas}$); and
- Fraction of N loss from runoff and leaching ($Frac_{runoff/leach}$).

Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. The activity data sources (except for population, TAM, and WMS, which were described above) are described below:

- Nex for all cattle except for calves were calculated by head for each state and animal type in the CEFM. Nex rates by animal mass for all other animals were determined using data from USDA's *Agricultural Waste Management Field Handbook* (USDA 1996 and 2008; ERG 2010b and 2010c) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) and IPCC (2006). American bison Nex were assumed to be the same as NOF bulls.[8]
- All N_2O emission factors (direct and indirect) were taken from IPCC (2006).
- Country-specific estimates for the fraction of N loss from volatilization ($Frac_{gas}$) and runoff and leaching ($Frac_{runoff/leach}$) were developed. $Frac_{gas}$ values were based on WMS-specific volatilization values as estimated from EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). $Frac_{runoff/leaching}$ values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Annex 3.11).

To estimate N_2O emissions for cattle (except for calves), the estimated amount of N excreted (kg per animal-year) that is managed in each WMS for each animal type, state, and year were taken from the CEFM. For calves and other animals, the amount of N excreted (kg per year) in manure in each WMS for each animal type, state, and year was calculated. The population (head) for each state and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the nitrogen excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EF_{WMS}, in kg N_2O-N per kg N) and the conversion factor of N_2O-N to N_2O. These emissions were summed over state, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year). See details in Step 6 of Annex 3.11.

Indirect N_2O emissions from volatilization (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization ($Frac_{gas}$) divided by 100, the emission factor for volatilization ($EF_{volatilization}$, in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Indirect N_2O emissions from runoff and leaching (kg N_2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching ($Frac_{runoff/leach}$) divided by 100, and the emission factor for runoff and leaching ($EF_{runoff/leach}$, in kg N_2O per kg N), and the conversion

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[8] Nex of American bison on grazing lands are accounted for and discussed in the Agricultural Soil Management source category and included under pasture, range and paddock (PRP) emissions. Because American bison are maintained entirely on unmanaged WMS and N_2O emissions from unmanaged WMS are not included in the Manure Management source category, there are no N_2O emissions from American bison included in the Manure Management source category.

factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions. See details in Step 6 of Annex 3.11.

Following these steps, direct and indirect N_2O emissions were summed to determine total N_2O emissions (kg N_2O per year) for the years 1990 to 2020.

Methodological approaches, changes to historic data, and other parameters were applied to the entire time series to ensure consistency in emissions estimates from 1990 through 2020. In some cases, the activity data source changed over the time series. For example, updated WMS distribution data were applied to 2016 for dairy cows and 2009 for swine. While previous data were from another data source, EPA updated with the more recent data source to reflect the best available current data. EPA assumed a linear interpolation distribution for years between the two data sources. Refer to Annex 3.11 for more details on data sources and methodology.

Refer to the Recalculations section below for details on updates implemented to improve accuracy, consistency, and/or completeness of the time series.

Uncertainty

An analysis (ERG 2003a) was conducted for the manure management emission estimates presented in the 1990 through 2001 Inventory (i.e., 2003 submission to the UNFCCC) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. The quantitative uncertainty analysis for this source category was performed in 2002 through the IPCC-recommended Approach 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state. While there are plans to update the uncertainty to reflect recent manure management updates and forthcoming changes (see Planned Improvements, below), at this time the uncertainty estimates were directly applied to the 2020 emission estimates.

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-8. Manure management CH_4 emissions in 2020 were estimated to be between 48.8 and 71.5 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2020 emission estimate of 59.6 MMT CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 16.5 and 24.4 MMT CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2020 emission estimate of 19.7 MMT CO_2 Eq.).

Table 5-8: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O (Direct and Indirect) Emissions from Manure Management (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	59.6	48.8	71.5	-18%	+20%
Manure Management	N_2O	19.7	16.5	24.4	-16%	+24%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Tier 2 activities focused on comparing estimates for the previous and current Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. In addition, manure N data were checked by comparing state-level data with bottom-up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and WMS type for the full time series, between national level estimates for N excreted, both for pasture and managed systems, and the sum of county estimates for the full time series. This was done to ensure consistency between excreted N within the manure management sector and those data provided to the managed soils sector. All errors identified were corrected.

Time-series data, including population, are validated by experts to ensure they are representative of the best available U.S.-specific data. The U.S.-specific values for TAM, Nex, VS, B_0, and MCF were also compared to the IPCC default values and validated by experts. Although significant differences exist in some instances, these differences are due to the use of U.S.-specific data and the differences in U.S. agriculture as compared to other countries. The U.S. manure management emission estimates use the most reliable country-specific data, which are more representative of U.S. animals and systems than the IPCC (2006) default values.

For additional verification of the 1990 to 2020 estimates, the implied CH_4 emission factors for manure management (kg of CH_4 per head per year) were compared against the default IPCC (2006) values. Table 5-9 presents the implied emission factors of kg of CH_4 per head per year used for the manure management emission estimates as well as the IPCC (2006) default emission factors. The U.S. implied emission factors fall within the range of the IPCC (2006) default values, except in the case of sheep, goats, and some years for horses and dairy cattle. The U.S. implied emission factors are greater than the IPCC (2006) default value for those animals due to the use of U.S.-specific data for typical animal mass and VS excretion. There is an increase in implied emission factors for dairy cattle and swine across the time series. This increase reflects the dairy cattle and swine industry trend towards larger farm sizes; large farms are more likely to manage manure as a liquid and therefore produce more CH_4 emissions.

Table 5-9: IPCC (2006) Implied Emission Factor Default Values Compared with Calculated Values for CH_4 from Manure Management (kg/head/year)

Animal Type	IPCC Default CH_4 Emission Factors (kg/head/year)[a]	Implied CH_4 Emission Factors (kg/head/year)						
		1990	2005	2016	2017	2018	2019	2020
Dairy Cattle	48-112	29.3	53.0	65.4	66.0	67.3	65.6	67.5
Beef Cattle	1-2	0.8	0.8	0.9	0.9	0.9	0.9	0.9
Swine	10-45	11.5	13.3	12.1	11.6	12.0	11.6	11.6
Sheep	0.19-0.37	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Goats	0.13-0.26	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Poultry	0.02-1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Horses	1.56-3.13	1.9	1.4	1.2	1.2	1.2	1.2	1.2
American Bison	NA	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Mules and Asses	0.76-1.14	0.4	0.4	0.4	0.4	0.4	0.4	0.4

NA (Not Applicable)

[a] Ranges reflect *2006 IPCC Guidelines* (Volume 4, Table 10.14) default emission factors for North America across different climate zones.

In addition, default IPCC (2006) emission factors for N_2O were compared to the U.S. Inventory implied N_2O emission factors. Default N_2O emission factors from the *2006 IPCC Guidelines* were used to estimate N_2O emission from each WMS in conjunction with U.S.-specific Nex values. The implied emission factors differed from the U.S. Inventory values due to the use of U.S.-specific Nex values and differences in populations present in each WMS throughout the time series.

Recalculations Discussion

The manure management emission estimates include the following recalculations:

- EPA revised the methodology for population distribution to states where USDA population data are withheld due to disclosure concerns (ERG 2021). The following animal population estimates were impacted:
    - Poultry in 1990 through 2018 (for several states that varied over the time series).
    - Sheep in 1990 through 2018 (for several states that varied over the time series).
    - Swine in 2010 through 2016 (for ID and WA).
- EPA updated the MCF for pasture to align with updated guidance from IPCC (2019).
- USDA updated raw animal population data which affected the following populations:
    - Swine in 2018 for select states.
    - Poultry in 2018 for select states.
    - Sheep in 2018 for select states.
- The following data were updated in the CEFM which impacted emissions in the manure inventory (see Section 5.1 for more details):
    - Milk fat data for dairy and beef cows were updated for 1990 through 2018 which affected VS and Nex for those animals and years.
    - Crude protein data were updated which affected Nex for feedlot animals for 2015 through 2018.
    - Annual calf birth and cattle population data were updated which impacted cattle populations for 2013 through 2018.
    - USDA revised cattle populations for various states which changed cattle populations from 2014 through 2018.

The cumulative effect of these recalculations had a medium impact on the overall manure management emission estimates. Over the time series:

- The average total emissions decreased by 4 percent from the previous Inventory. The changes ranged from the smallest decrease, 2.6 percent (2.0 MMT CO_2 Eq.), in 2017, to the largest decrease, 4.6 percent (2.4 MMT CO_2 Eq.), in 1990.
- The average CH_4 emissions decreased by 5 percent from the previous Inventory. The changes ranged from the smallest decrease 3.7 percent (2.3 MMT CO_2 Eq.), in 2018, to the largest decrease, 6.2 percent (2.3 MMT CO_2 Eq.), in 1990.
- The average N_2O emissions decreased by 0.2 percent from the previous Inventory. The changes ranged from the smallest decrease 0.8 percent (0.2 MMT CO_2 Eq.), in 2018, to the largest increase, 1.8 percent (0.3 MMT CO_2 Eq.), in 2017.

Planned Improvements

Regular annual data reviews and updates are necessary to maintain an emissions inventory that reflects the current base of knowledge. EPA conducts the following list of regular annual assessments of data availability when updating the estimates to extend time series each year. EPA is actively pursuing the following updates for the either the 2023 or 2024 Inventory submission:

- Continuing to investigate new sources of WMS data. EPA is working with the USDA Natural Resources Conservation Service to collect data for potential improvements to the Inventory.
- Determining appropriate updates to other default N_2O emission factors to reflect IPCC (2019).

Many of the improvements identified below are major updates and may take multiple years to fully implement. Potential improvements (long-term improvements) for future Inventory years include:

- Revising the anaerobic digestion estimates to estimate CH_4 emissions *reductions* due to the use of anaerobic digesters (the Inventory currently estimates only emissions from anaerobic digestion systems).
- Investigating the updated IPCC *2019 Refinement* default N_2O emissions factor for anaerobic digesters. Historically, EPA has not estimated N_2O emissions from digesters as the default guidance was no emissions. Incorporating AgSTAR data for N_2O emissions, like CH_4 emissions, is a longer-term goal for EPA.
- Investigating updates to the current AD MCFs based on IPCC (2019).
- Determining if there are revisions to the U.S.-specific method for calculating liquid systems for MCFs based on updated guidance from the IPCC *2019 Refinement*.
- Investigating improved emissions estimate methodologies for swine pit systems with less than one month of storage (the recently updated swine WMS data included this WMS category).
- Improving collaboration with the Enteric Fermentation source category estimates. For future Inventories, it may be beneficial to have the CEFM and Manure Management calculations in the same model, as they rely on much of the same activity data and on each other's outputs to properly calculate emissions.
- Revising the uncertainty analysis to address changes that have been implemented to the CH_4 and N_2O estimates. EPA plans to align the timing of the updated Manure Management uncertainty analysis with the uncertainty analysis for Enteric Fermentation.

EPA is actively pursuing the following updates but notes that implementation may be based on available resources and data availability:

- Updating the B_0 data used in the Inventory, as data become available. EPA is conducting outreach with counterparts from USDA as to available data and research on B_0.
- Comparing CH_4 and N_2O emission estimates with estimates from other models and more recent studies and compare the results to the Inventory.
- Comparing manure management emission estimates with on-farm measurement data to identify opportunities for improved estimates.
- Comparing VS and Nex data to literature data to identify opportunities for improved estimates.

5.3 Rice Cultivation (CRF Source Category 3C)

Most of the world's rice is grown on flooded fields (Baicich 2013) that create anaerobic conditions leading to CH_4 production through a process known as methanogenesis. Approximately 60 to 90 percent of the CH_4 produced by methanogenic bacteria in flooded rice fields is oxidized in the soil and converted to CO_2 by methanotrophic bacteria. The remainder is emitted to the atmosphere (Holzapfel-Pschorn et al. 1985; Sass et al. 1990) or transported as dissolved CH_4 into groundwater and waterways (Neue et al. 1997). Methane is transported to the atmosphere primarily through the rice plants, but some CH_4 also escapes via ebullition (i.e., bubbling through the water) and to a much lesser extent by diffusion through the water (van Bodegom et al. 2001).

Water management is arguably the most important factor affecting CH_4 emissions in rice cultivation, and improved water management has the largest potential to mitigate emissions (Yan et al. 2009). Upland rice fields are not flooded, and therefore do not produce CH_4, but large amounts of CH_4 can be emitted in continuously irrigated fields, which is the most common practice in the United States (USDA 2012). Single or multiple aeration events with drainage of a field during the growing season can significantly reduce these emissions (Wassmann et al. 2000a), but drainage may also increase N_2O emissions. Deepwater rice fields (i.e., fields with flooding depths greater than one meter, such as natural wetlands) tend to have fewer living stems reaching the soil, thus reducing the amount of CH_4 transport to the atmosphere through the plant compared to shallow-flooded systems (Sass 2001).

Other management practices also influence CH_4 emissions from flooded rice fields including rice residue straw management and application of organic amendments, in addition to cultivar selection due to differences in the amount of root exudates[9] among rice varieties (Neue et al. 1997). These practices influence the amount of organic matter available for methanogenesis, and some practices, such as mulching rice straw or composting organic amendments, can reduce the amount of labile carbon and limit CH_4 emissions (Wassmann et al. 2000b). Fertilization practices also influence CH_4 emissions, particularly the use of fertilizers with sulfate (Wassmann et al. 2000b; Linquist et al. 2012), which can reduce CH_4 emissions. Other environmental variables also impact the methanogenesis process such as soil temperature and soil type. Soil temperature regulates the activity of methanogenic bacteria, which in turn affects the rate of CH_4 production. Soil texture influences decomposition of soil organic matter, but is also thought to have an impact on oxidation of CH_4 in the soil (Sass et al. 1994).

Rice is currently cultivated in thirteen states, including Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee and Texas. Soil types, rice varieties, and cultivation practices vary across the United States, but most farmers apply fertilizers and do not harvest crop residues. In addition, a second, ratoon rice crop is grown in the Southeastern region of the country. Ratoon crops are produced from regrowth of the stubble remaining after the harvest of the first rice crop. Methane emissions from ratoon crops are higher than those from the primary crops due to the increased amount of labile organic matter available for anaerobic decomposition in the form of relatively fresh crop residue straw. Emissions tend to be higher in rice fields if the residues have been in the field for less than 30 days before planting the next rice crop (Lindau and Bollich 1993; IPCC 2006; Wang et al. 2013).

A combination of Tier 1 and 3 methods are used to estimate CH_4 emissions from rice cultivation across most of the time series, while a surrogate data method has been applied to estimate national emissions for 2016 to 2020 in this Inventory due to lack of data in the later years of the time series. National emission estimates based on surrogate data will be recalculated in a future Inventory with the Tier 1 and 3 methods as data becomes available.

Overall, rice cultivation is a minor source of CH_4 emissions in the United States relative to other source categories (see Table 5-10, Table 5-11, and Figure 5-3). Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri and Texas. In 2020, CH_4 emissions from rice cultivation were 15.7 MMT CO_2 Eq. (630 kt). Annual emissions fluctuate between 1990 and 2020, which is largely due to differences in the amount of rice harvested areas over time, which has been decreasing over the past two decades. Consequently, emissions in 2020 are 2 percent lower than emissions in 1990.

Table 5-10: CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq.)

State	1990		2005		2016	2017	2018	2019	2020
Arkansas	5.4		7.9		NE	NE	NE	NE	NE
California	3.3		3.4		NE	NE	NE	NE	NE
Florida	+		+		NE	NE	NE	NE	NE
Illinois	+		+		NE	NE	NE	NE	NE
Kentucky	+		+		NE	NE	NE	NE	NE

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[9] The roots of rice plants add organic material to the soil through a process called "root exudation." Root exudation is thought to enhance decomposition of the soil organic matter and release nutrients that the plant can absorb and use to stimulate more production. The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

Louisiana	2.6	2.8	NE	NE	NE	NE	NE
Minnesota	+	0.1	NE	NE	NE	NE	NE
Mississippi	1.1	1.4	NE	NE	NE	NE	NE
Missouri	0.6	1.1	NE	NE	NE	NE	NE
New York	+	+	NE	NE	NE	NE	NE
South Carolina	+	+	NE	NE	NE	NE	NE
Tennessee	+	+	NE	NE	NE	NE	NE
Texas	3.0	1.3	NE	NE	NE	NE	NE
Total	**16.0**	**18.0**	**15.8**	**14.9**	**15.6**	**15.1**	**15.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

NE (Not Estimated). State-level emissions are not estimated for 2016 through 2020 in this Inventory because data are unavailable. A surrogate data method is used to estimate emissions for these years and are produced only at the national scale.

Note: Totals may not sum due to independent rounding.

Table 5-11: CH_4 Emissions from Rice Cultivation (kt)

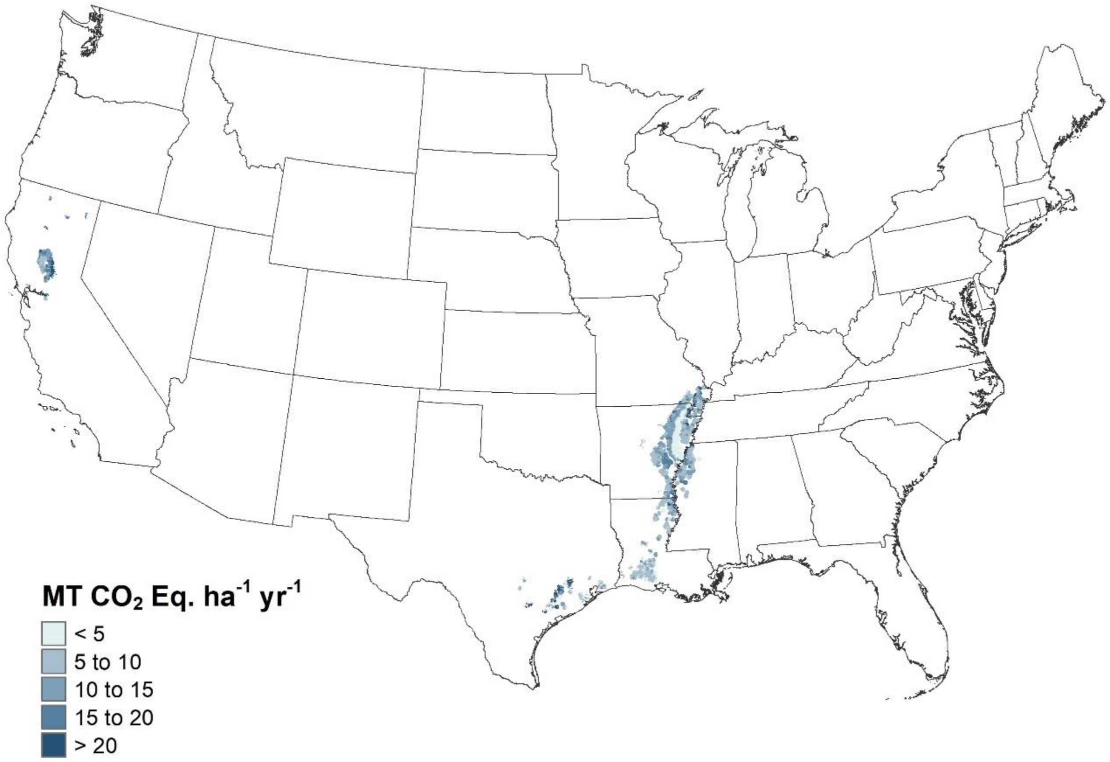
State	1990	2005	2016	2017	2018	2019	2020
Arkansas	216	315	NE	NE	NE	NE	NE
California	131	134	NE	NE	NE	NE	NE
Florida	+	1	NE	NE	NE	NE	NE
Illinois	+	+	NE	NE	NE	NE	NE
Kentucky	+	+	NE	NE	NE	NE	NE
Louisiana	103	113	NE	NE	NE	NE	NE
Minnesota	1	2	NE	NE	NE	NE	NE
Mississippi	45	55	NE	NE	NE	NE	NE
Missouri	22	45	NE	NE	NE	NE	NE
New York	+	+	NE	NE	NE	NE	NE
South Carolina	+	+	NE	NE	NE	NE	NE
Tennessee	+	+	NE	NE	NE	NE	NE
Texas	122	54	NE	NE	NE	NE	NE
Total	**640**	**720**	**631**	**596**	**623**	**602**	**630**

+ Does not exceed 0.5 kt.

NE (Not Estimated). State-level emissions are not estimated for 2016 through 2020 in this Inventory because data are unavailable. A surrogate data method is used to estimate emissions for these years and are produced only at the national scale.

Note: Totals may not sum due to independent rounding.

Figure 5-3: Annual CH_4 Emissions from Rice Cultivation, 2015



Note: Only national-scale emissions are estimated for 2016 through 2020 in this Inventory using the surrogate data method described in the Methodology section; therefore, the fine-scale emission patterns in this map are based on the estimates for 2015.

Methodology and Time-Series Consistency

The methodology used to estimate CH_4 emissions from rice cultivation is based on a combination of IPCC Tier 1 and 3 approaches. The Tier 3 method utilizes the DayCent process-based model to estimate CH_4 emissions from rice cultivation (Cheng et al. 2013), and has been tested in the United States (see Annex 3.12) and Asia (Cheng et al. 2013, 2014). The model simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH_4, as well as CH_4 transport through the plant and via ebullition (Cheng et al. 2013). The method captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season. In addition to CH_4 emissions, DayCent simulates soil C stock changes and N_2O emissions (Parton et al. 1987 and 1998; Del Grosso et al. 2010), and allows for a seamless set of simulations for crop rotations that include both rice and non-rice crops.

The Tier 1 method is applied to estimate CH_4 emissions from rice when grown in rotation with crops that are not simulated by DayCent, such as vegetable crops. The Tier 1 method is also used for areas converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland, and settlements. In addition, the Tier 1 method is used to estimate CH_4 emissions from organic soils (i.e., Histosols) and from areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume). The Tier 3 method using DayCent has not been fully tested for estimating emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils.

The Tier 1 method for estimating CH_4 emissions from rice production utilizes a default base emission rate and scaling factors (IPCC 2006). The base emission rate represents emissions for continuously flooded fields with no organic amendments. Scaling factors are used to adjust the base emission rate for water management and organic amendments that differ from continuous flooding with no organic amendments. The method accounts for pre-season and growing season flooding; types and amounts of organic amendments; and the number of rice production seasons within a single year (i.e., single cropping, ratooning, etc.). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[10]

Rice cultivation areas are based on cropping and land use histories recorded in the USDA National Resources Inventory (NRI) survey (USDA-NRCS 2018). The NRI is a statistically-based sample of all non-federal land, and includes 489,178 survey locations in agricultural land for the conterminous United States and Hawaii of which 1,960 include one or more years of rice cultivation. The Tier 3 method is used to estimate CH_4 emissions from 1,655 of the NRI survey locations, and the remaining 305 survey locations are estimated with the Tier 1 method. Each NRI survey location is associated with an “expansion factor” that allows scaling of CH_4 emission to the entire land base with rice cultivation (i.e., each expansion factor represents the amount of area with the same land-use/management history as the survey location). Land-use and some management information in the NRI (e.g., crop type, soil attributes, and irrigation) were collected on a 5-year cycle beginning in 1982, along with cropping rotation data in 4 out of 5 years for each 5-year time period (i.e., 1979 to 1982, 1984 to 1987, 1989 to 1992, and 1994 to 1997). The NRI program began collecting annual data in 1998, with data currently available through 2015 (USDA-NRCS 2018). The current Inventory only uses NRI data through 2015 because newer data are not available, but will be incorporated when additional years of data are released by USDA-NRCS. The harvested rice areas in each state are presented in Table 5-12.

Table 5-12: Rice Area Harvested (1,000 Hectares)

State/Crop	1990	2005	2016	2017	2018	2019	2020
Arkansas	600	784	NE	NE	NE	NE	NE
California	249	236	NE	NE	NE	NE	NE
Florida	0	4	NE	NE	NE	NE	NE
Illinois	0	0	NE	NE	NE	NE	NE
Kentucky	0	0	NE	NE	NE	NE	NE
Louisiana	381	402	NE	NE	NE	NE	NE
Minnesota	4	9	NE	NE	NE	NE	NE
Mississippi	123	138	NE	NE	NE	NE	NE
Missouri	48	94	NE	NE	NE	NE	NE
New York	1	0	NE	NE	NE	NE	NE
South Carolina	0	0	NE	NE	NE	NE	NE
Tennessee	0	1	NE	NE	NE	NE	NE
Texas	302	118	NE	NE	NE	NE	NE
Total	**1,707**	**1,788**	**NE**	**NE**	**NE**	**NE**	**NE**

NE (Not Estimated). State-level area data are not available for 2016 through 2020 but will be added in a future Inventory with release of new NRI survey data.

Note: Totals may not sum due to independent rounding.

The Southeastern states have sufficient growing periods for a ratoon crop in some years (Table 5-13). For example, the growing season length is occasionally sufficient for ratoon crops to be grown on about 1 percent of the rice fields in Arkansas. No data are available about ratoon crops in Missouri or Mississippi, and the average amount of ratooning in Arkansas was assigned to these states. Ratoon cropping occurs much more frequently in Louisiana (LSU 2015 for years 2000 through 2013, 2015) and Texas (TAMU 2015 for years 1993 through 2015), averaging 32 percent and 45 percent of rice acres planted, respectively. Florida also has a large fraction of area with a ratoon crop (49 percent). Ratoon rice crops are not grown in California.

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[10] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

Table 5-13: Average Ratooned Area as Percent of Primary Growth Area (Percent)

State	1990-2015
Arkansas[a]	1%
California	0%
Florida[b]	49%
Louisiana[c]	32%
Mississippi[a]	1%
Missouri[a]	1%
Texas[d]	45%

[a] Arkansas: *1990–2000* (Slaton 1999 through 2001); *2001–2011* (Wilson 2002 through 2007, 2009 through 2012); *2012–2013* (Hardke 2013, 2014). Estimates of ratooning for Missouri and Mississippi are based on the data from Arkansas.

[b] Florida - Ratoon: *1990–2000* (Schueneman 1997, 1999 through 2001); *2001* (Deren 2002); *2002–2003* (Kirstein 2003 through 2004, 2006); *2004* (Cantens 2004 through 2005); *2005–2013* (Gonzalez 2007 through 2014).

[c] Louisiana: *1990–2013* (Linscombe 1999, 2001 through 2014).

[d] Texas: *1990–2002* (Klosterboer 1997, 1999 through 2003); *2003–2004* (Stansel 2004 through 2005); *2005* (Texas Agricultural Experiment Station 2006); *2006–2013* (Texas Agricultural Experiment Station 2007 through 2014).

While rice crop production in the United States includes a minor amount of land with mid-season drainage or alternate wet-dry periods, the majority of rice growers use continuously flooded water management systems (Hardke 2015; UCCE 2015; Hollier 1999; Way et al. 2014). Therefore, continuous flooding was assumed in the DayCent simulations and the Tier 1 method. Variation in flooding can be incorporated in future Inventories if water management data are collected.

Winter flooding is another key practice associated with water management in rice fields, and the impact of winter flooding on CH_4 emissions is addressed in the Tier 3 and Tier 1 analyses. Flooding is used to prepare fields for the next growing season, and to create waterfowl habitat (Young 2013; Miller et al. 2010; Fleskes et al. 2005). Fitzgerald et al. (2000) suggests that as much as 50 percent of the annual emissions may occur during winter flooding. Winter flooding is a common practice with an average of 34 percent of fields managed with winter flooding in California (Miller et al. 2010; Fleskes et al. 2005), and approximately 21 percent of the fields managed with winter flooding in Arkansas (Wilson and Branson 2005 and 2006; Wilson and Runsick 2007 and 2008; Wilson et al. 2009 and 2010; Hardke and Wilson 2013 and 2014; Hardke 2015). No data are available on winter flooding for Texas, Louisiana, Florida, Missouri, or Mississippi. For these states, the average amount of flooding is assumed to be similar to Arkansas. In addition, the amount of flooding is assumed to be relatively constant over the Inventory time series.

A surrogate data method is used to estimate emissions from 2016 to 2020 associated with the rice CH_4 emissions for Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2015, which were derived using the Tier 1 and 3 methods (Brockwell and Davis 2016). Surrogate data are based on rice commodity statistics from USDA-NASS.[11] See Box 5-2 for more information about the surrogate data method.

Box 5-2: Surrogate Data Method

An approach to extend the time series is needed to estimate emissions from Rice Cultivation because there are gaps in activity data at the end of the time series. This is mainly due to the fact that the National Resources Inventory (NRI) does not release data every year, and the NRI is a key data source for estimating greenhouse gas emissions.

A surrogate data method has been selected to impute missing emissions at the end of the time series. A linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the observed 1990 to 2015 emissions data that has

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[11] See https://quickstats.nass.usda.gov/.

been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., CH_4 emissions), Xβ is the surrogate data that is used to predict the missing emissions data, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the observed data for 1990 to 2015 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2016 to 2020.

A critical issue in using splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions with related information without compiling the full inventory. For example, predicting CH_4 emissions will increase the total variation in the emission estimates for these specific years, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2015).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series based on the emissions data from 1990 to 2015. This extrapolation method is consistent with data splicing methods in IPCC (2006).

Uncertainty

Sources of uncertainty in the Tier 3 method include management practices, uncertainties in model structure (i.e., algorithms and parameterization), and variance associated with the NRI sample. Sources of uncertainty in the IPCC (2006) Tier 1 method include the emission factors, management practices, and variance associated with the NRI sample. A Monte Carlo analysis was used to propagate uncertainties in the Tier 1 and 3 methods. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method (See Box 5-2 for information about propagating uncertainty with the surrogate data method). The uncertainties from the Tier 1 and 3 approaches are combined to produce the final CH_4 emissions estimate using simple error propagation (IPCC 2006). Additional details on the uncertainty methods are provided in Annex 3.12. Rice cultivation CH_4 emissions in 2020 were estimated to be between 4.0 and 27.5 MMT CO_2 Eq. at a 95 percent confidence level, which indicates a range of 75 percent below to 75 percent above the 2020 emission estimate of 15.7 MMT CO_2 Eq. (see Table 5-14).

Table 5-14: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (MMT CO_2 Eq. and Percent)

Source	Inventory Method	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
				Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	Tier 3	CH_4	13.2	1.5	24.9	-88%	+88%
Rice Cultivation	Tier 1	CH_4	2.5	1.3	3.7	-48%	+48%
Rice Cultivation	**Total**	**CH_4**	**15.7**	**4.0**	**27.5**	**-75%**	**+75%**

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. Quality control measures include checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors.

Model results are compared to field measurements to verify if results adequately represent CH_4 emissions. The comparisons included over 17 long-term experiments, representing about 238 combinations of management treatments across all the sites. A statistical relationship was developed to assess uncertainties in the model structure, adjusting the estimates for model bias and assessing precision in the resulting estimates (methods are described in Ogle et al. 2007). See Annex 3.12 for more information.

Recalculations Discussion

No recalculations were done in this Inventory.

Planned Improvements

A key planned improvement for rice cultivation is to fill several gaps in the management activity including compiling new data on water management, organic amendments and ratooning practices in rice cultivation systems. This improvement is expected to be completed for the next Inventory, but may not be prioritized considering overall improvements to make best use of available resources.

5.4 Agricultural Soil Management (CRF Source Category 3D)

Nitrous oxide is naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989).[12] Mineral N is made available in soils through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the

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[12] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to N_2. Nitrous oxide is a gaseous intermediate product in the reaction sequence of nitrification and denitrification.

atmosphere.[13] Several agricultural activities increase mineral N availability in soils that lead to direct N_2O emissions at the site of a management activity (see Figure 5-4) (Mosier et al. 1998). These activities include synthetic N fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (N-fixing legumes and non-legume crops and forages); and drainage of organic soils[14] (i.e., Histosols) (IPCC 2006). Additionally, agricultural soil management activities, including irrigation, drainage, tillage practices, cover crops, and fallowing of land, can influence N mineralization from soil organic matter and levels of asymbiotic N fixation. Indirect emissions of N_2O occur when N is transported from a site and is subsequently converted to N_2O; there are two pathways for indirect emissions: (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water.[15] Direct and indirect emissions from agricultural lands are included in this section (i.e., cropland and grassland as defined in Section 6.1 Representation of the U.S. Land Base). Nitrous oxide emissions from Forest Land and Settlements soils are found in Sections 6.2 and 6.10, respectively.

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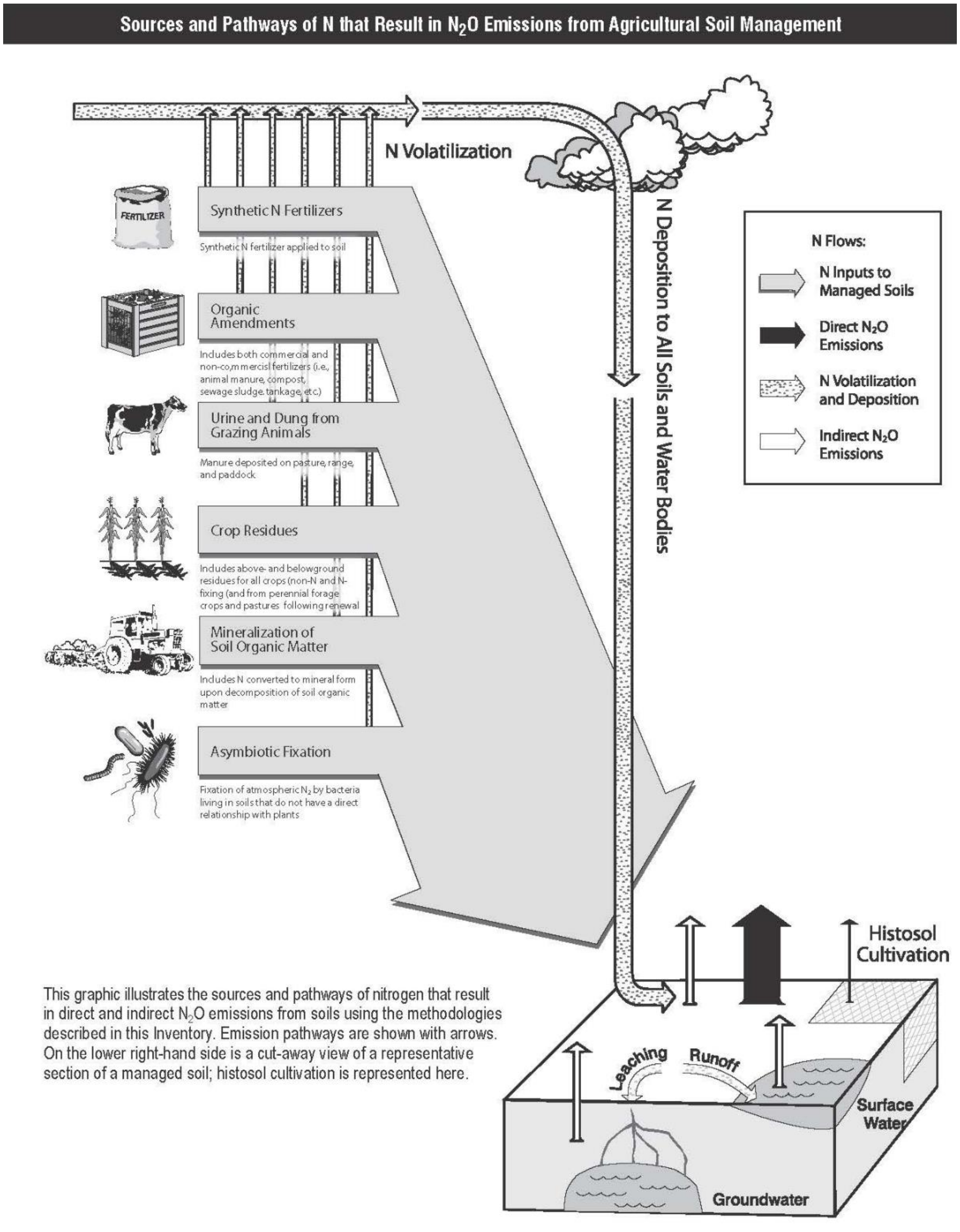
[13] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[14] Drainage of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby increasing N_2O emissions from these soils.

[15] These processes entail volatilization of applied or mineralized N as NH_3 and NO_x, transformation of these gases in the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate NH_4^+, nitric acid (HNO_3), and NO_x. In addition, hydrological processes lead to leaching and runoff of NO_3^- that is converted to N_2O in aquatic systems, e.g., wetlands, rivers, streams and lakes. Note: N_2O emissions are not estimated for aquatic systems associated with N inputs from terrestrial systems in order to avoid double-counting.

Figure 5-4: Sources and Pathways of N that Result in N_2O Emissions from Agricultural Soil Management



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils using the methodologies described in this Inventory. Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions in 2020 are 316.2 MMT CO_2 Eq. (1,061 kt) (see Table 5-15 and Table 5-16). Annual N_2O emissions from agricultural soils are 0.1 percent greater in 2020 compared to 1990, but emissions fluctuated between 1990 and 2020 due to inter-annual variability largely associated with weather patterns, synthetic fertilizer use, and crop production. From 1990 to 2020, cropland accounted for 68 percent of total direct emissions on average from agricultural soil management, while grassland accounted for 32 percent. On average, 78 percent of indirect emissions are from croplands and 22 percent from grasslands. Estimated direct and indirect N_2O emissions by sub-source category are shown in Table 5-17 and Table 5-18.

Table 5-15: N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Direct	**272.6**	**272.9**	**282.0**	**280.8**	**286.4**	**290.9**	**271.7**
Cropland	186.0	183.8	191.0	190.6	195.2	196.5	187.4
Grassland	86.6	89.1	91.0	90.3	91.3	94.4	84.3
Indirect	**43.5**	**40.9**	**48.9**	**47.4**	**52.5**	**54.4**	**44.6**
Cropland	34.2	31.6	38.9	37.4	42.4	43.9	35.4
Grassland	9.2	9.3	10.0	10.0	10.1	10.5	9.2
Total	**316.0**	**313.8**	**330.8**	**328.3**	**338.9**	**345.3**	**316.2**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-16: N_2O Emissions from Agricultural Soils (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Direct	**915**	**916**	**946**	**942**	**961**	**976**	**912**
Cropland	624	617	641	640	655	659	629
Grassland	291	299	305	303	306	317	283
Indirect	**146**	**137**	**164**	**159**	**176**	**182**	**150**
Cropland	115	106	130	126	142	147	119
Grassland	31	31	34	34	34	35	31
Total	**1,060**	**1,053**	**1,110**	**1,102**	**1,137**	**1,159**	**1,061**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Table 5-17: Direct N_2O Emissions from Agricultural Soils by Land Use Type and N Input Type (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Cropland	**185.9**	**183.7**	**191.0**	**190.5**	**195.1**	**196.5**	**187.3**
Mineral Soils	**182.1**	**180.0**	**187.6**	**187.1**	**191.7**	**193.1**	**183.9**
Synthetic Fertilizer	58.9	60.1	65.7	65.4	66.8	67.1	63.8
Organic Amendment[a]	12.8	13.1	14.7	14.5	14.4	14.3	13.9
Residue N[b]	40.7	41.0	41.2	41.2	42.3	42.7	40.8
Mineralization and Asymbiotic Fixation	69.8	65.8	66.0	66.1	68.2	68.9	65.4
Drained Organic Soils	**3.8**	**3.7**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Grassland	**86.7**	**89.2**	**91.0**	**90.3**	**91.3**	**94.4**	**84.3**
Mineral Soils	**84.2**	**86.7**	**88.5**	**87.8**	**88.8**	**91.9**	**81.9**
Synthetic Fertilizer	+	+	+	+	+	+	+
PRP Manure	14.5	13.6	13.0	13.0	13.1	13.4	12.4
Managed Manure[c]	+	+	+	+	+	+	+
Biosolids (i.e., treated Sewage Sludge)	0.2	0.5	0.6	0.6	0.6	0.7	0.7
Residue N[d]	29.8	30.9	31.6	31.3	31.7	32.8	29.0
Mineralization and Asymbiotic Fixation	39.6	41.8	43.3	42.9	43.4	45.0	39.8
Drained Organic Soils	**2.5**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total	**272.6**	**272.9**	**282.0**	**280.8**	**286.4**	**290.9**	**271.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Organic amendment inputs include managed manure, daily spread manure, and commercial organic fertilizers (i.e., dried blood, dried manure, tankage, compost, and other).

[b] Cropland residue N inputs include N in unharvested legumes as well as crop residue N.

[c] Managed manure inputs include managed manure and daily spread manure amendments that are applied to grassland soils.

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[d] Grassland residue N inputs include N in ungrazed legumes as well as ungrazed grass residue N.

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

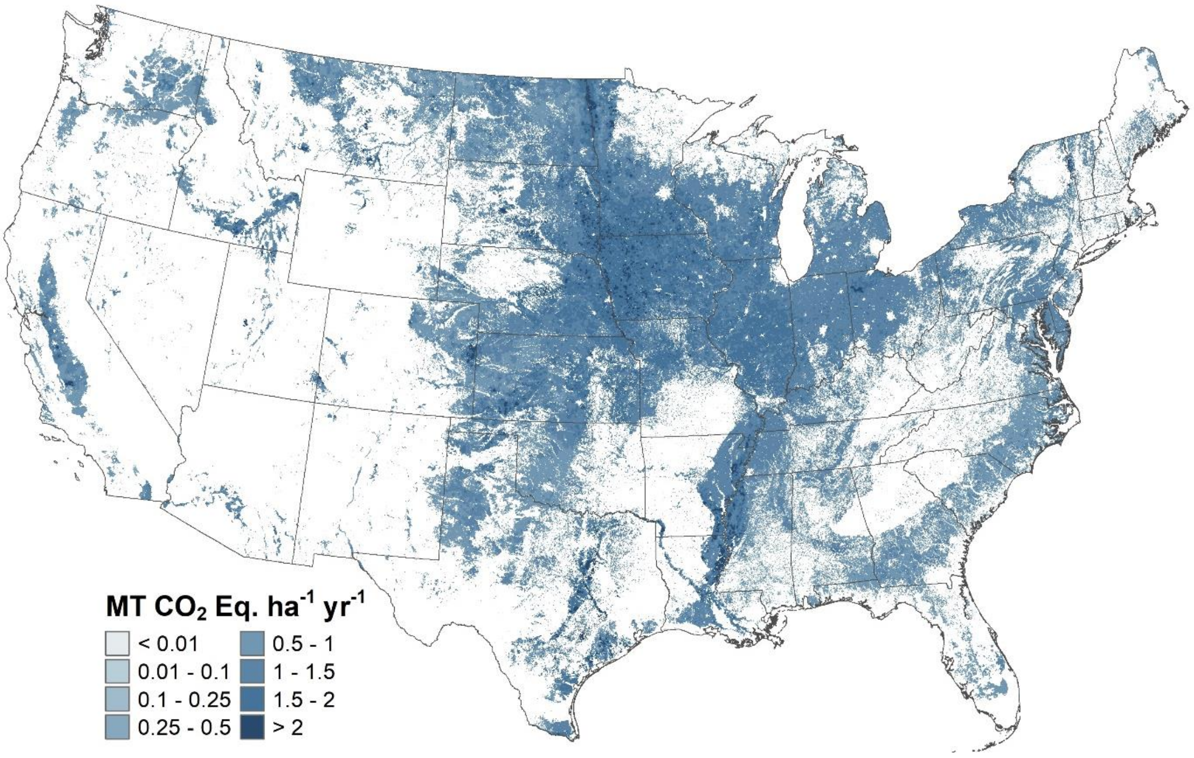
Table 5-18: Indirect N_2O Emissions from Agricultural Soils (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
Cropland	**34.2**	**31.6**	**38.9**	**37.4**	**42.4**	**43.9**	**35.4**
Volatilization & Atm. Deposition	6.5	7.3	8.1	7.9	8.0	8.0	7.6
Surface Leaching & Run-Off	27.8	24.4	30.8	29.5	34.4	35.9	27.8
Grassland	**9.2**	**9.3**	**10.0**	**10.0**	**10.1**	**10.5**	**9.2**
Volatilization & Atm. Deposition	3.6	3.7	3.5	3.6	3.6	3.7	3.5
Surface Leaching & Run-Off	5.6	5.6	6.5	6.4	6.5	6.8	5.7
Total	**43.5**	**40.9**	**48.9**	**47.4**	**52.5**	**54.4**	**44.6**

Notes: Estimates after 2015 are based on a data splicing method (See Methodology section). Totals may not sum due to independent rounding.

Figure 5-5 and Figure 5-6 show regional patterns for direct N_2O emissions. Figure 5-7 and Figure 5-8 show indirect N_2O emissions from volatilization, and Figure 5-9 and Figure 5-10 show the indirect N_2O emissions from leaching and runoff in croplands and grasslands, respectively.

Figure 5-5: Croplands, 2015 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

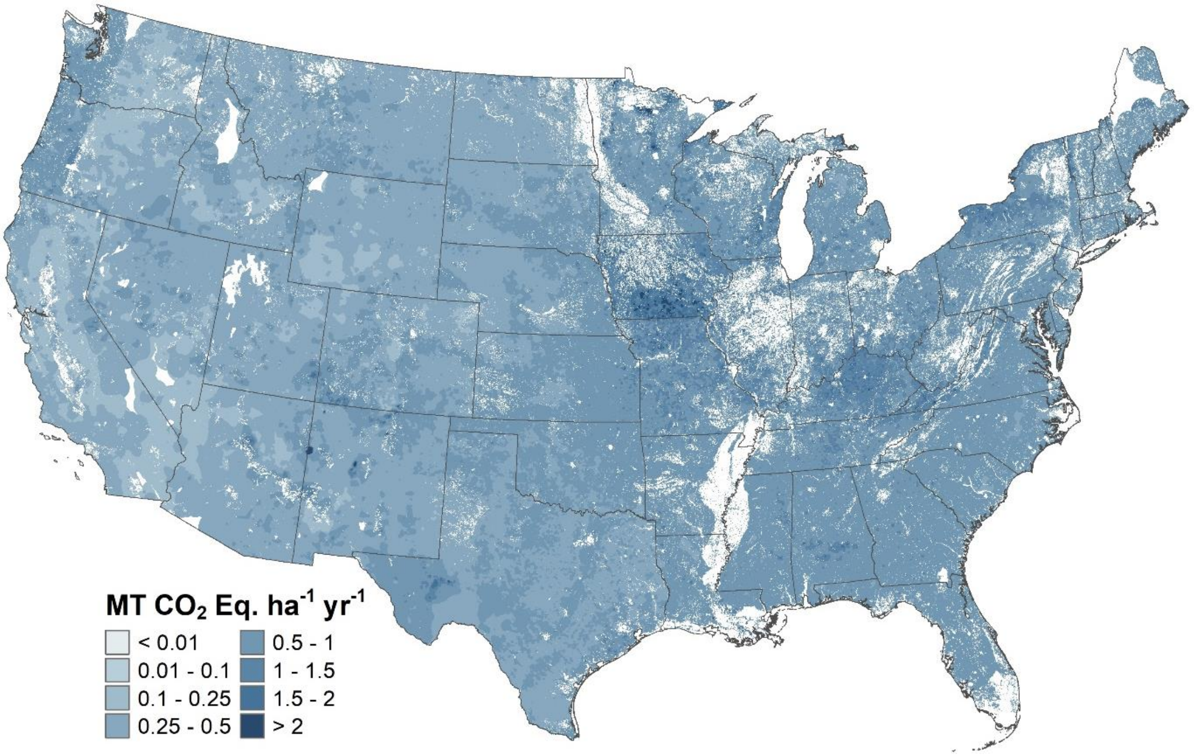


Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Direct N_2O emissions from croplands occur throughout all of the cropland regions but tend to be high in the Midwestern Corn Belt Region (Illinois, Iowa, Indiana, Ohio, southern Minnesota and Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean crops (see Figure 5-5). Kansas, South Dakota and North Dakota have relatively high emissions from large areas of crop production that are found in the Great Plains region. Emissions are also high in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado through Nebraska, Snake River Valley in Idaho and the Central Valley in California. Direct emissions are low in many parts of the eastern United States because only a small portion of land is cultivated, and in many western states where rainfall and access to irrigation water are limited.

Direct emissions from grasslands are more evenly distributed throughout the United States (see Figure 5-6), but total emissions tend be highest in the Great Plains and western United States where a large proportion of the land is dominated by grasslands with cattle and sheep grazing. However, there are relatively large emissions from local areas in the eastern United States, particularly Kentucky and Tennessee, in addition to areas in Missouri and Iowa, where there can be higher rates of Pasture/Range/Paddock (PRP) manure N additions on a relatively small amount of pasture. These areas have greater stocking rates of livestock per unit of area, compared to other regions of the United States.

Figure 5-6: Grasslands, 2015 Annual Direct N_2O Emissions Estimated Using the Tier 3 DayCent Model

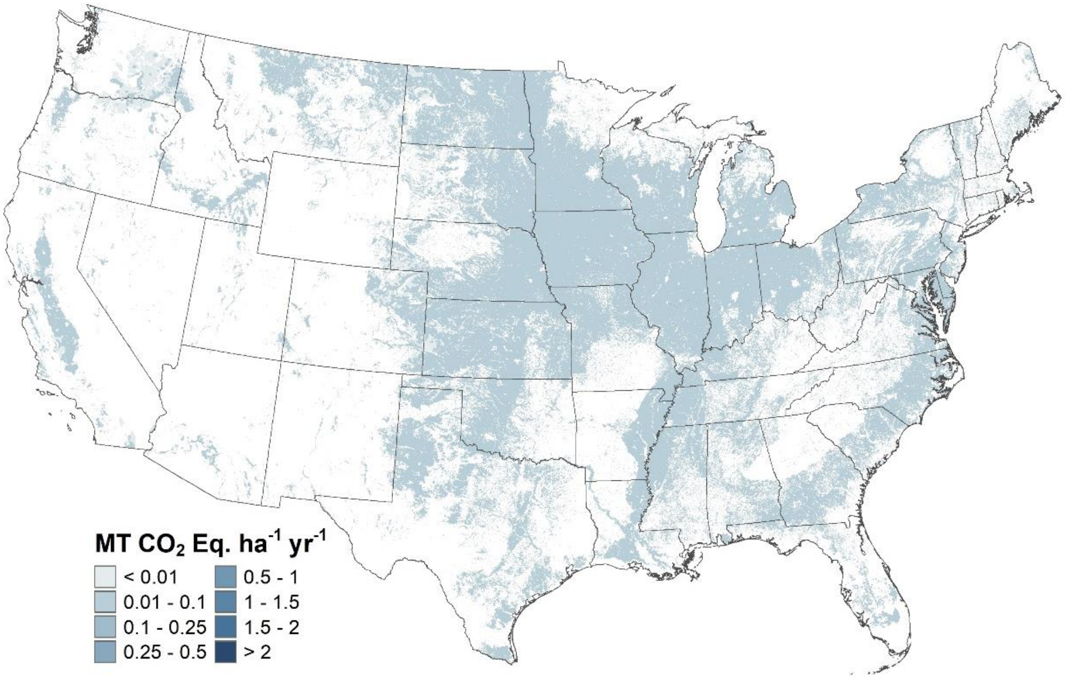


Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Indirect N_2O emissions from volatilization in croplands have a similar pattern as the direct N_2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin and Great Plains. Indirect N_2O emissions from volatilization in grasslands are higher in the Southeastern United States, along with portions of the Mid-Atlantic and southern Iowa. The higher emissions in this region are mainly due to large additions of PRP manure N on relatively small but productive pastures that support intensive grazing, which in turn, stimulates NH_3 volatilization.

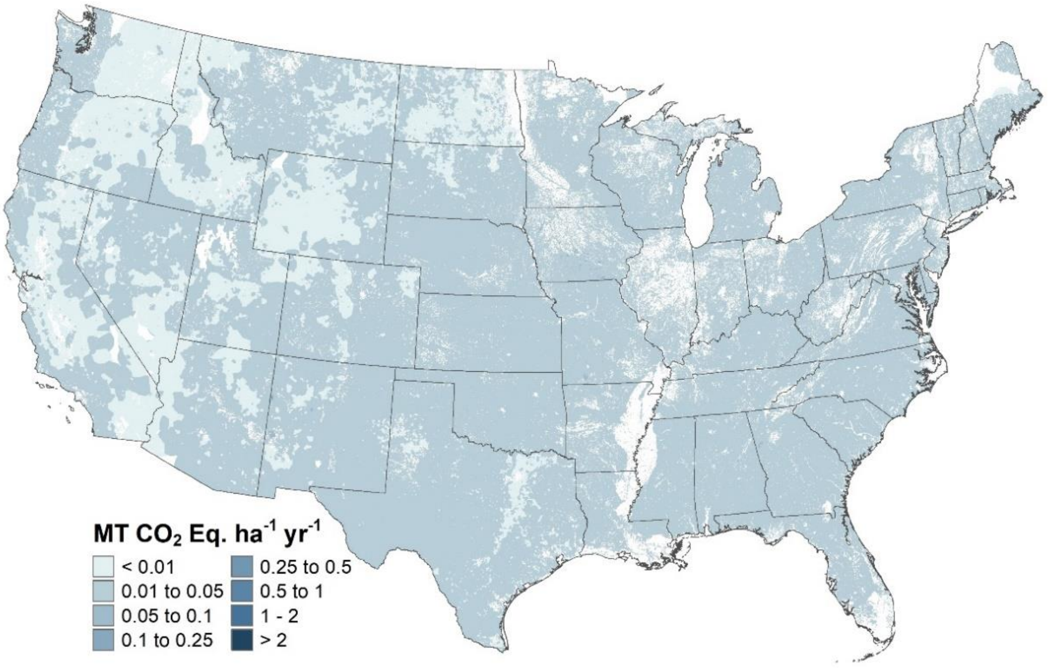
Indirect N_2O emissions from surface runoff and leaching of applied/mineralized N in croplands is highest in the Midwestern Corn Belt. There are also relatively high emissions associated with N management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states. In addition, areas of high emissions occur in portions of the Great Plains that have relatively large areas of irrigated croplands with high leaching rates of applied/mineralized N. Indirect N_2O emissions from surface runoff and leaching of applied/mineralized N in grasslands are higher in the eastern United States and coastal Northwest region. These regions have greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Figure 5-7: Croplands, 2015 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



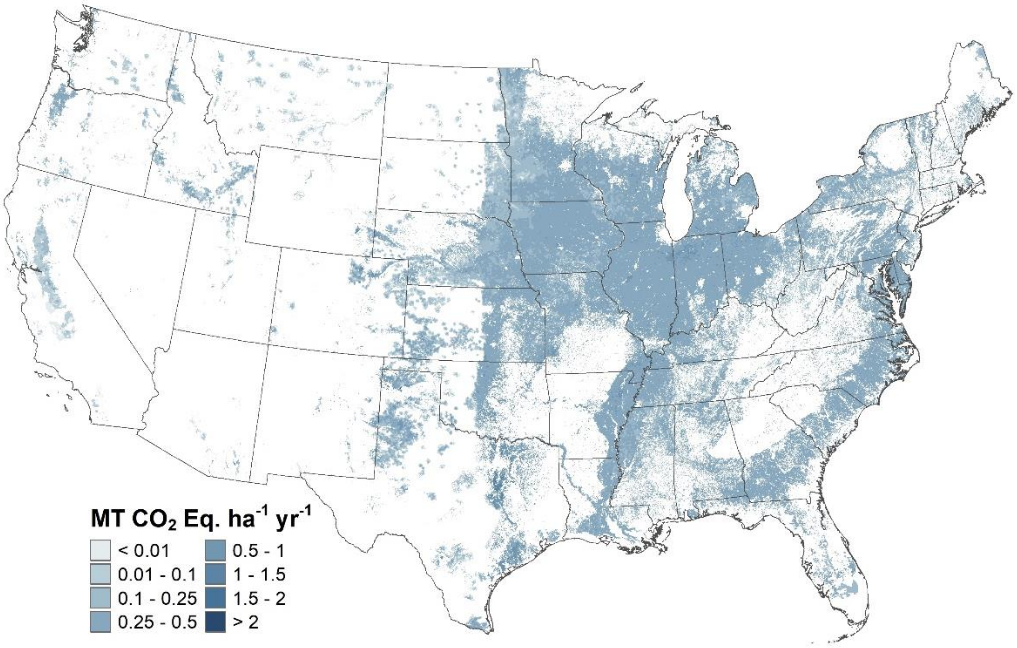
Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-8: Grasslands, 2015 Annual Indirect N_2O Emissions from Volatilization Using the Tier 3 DayCent Model



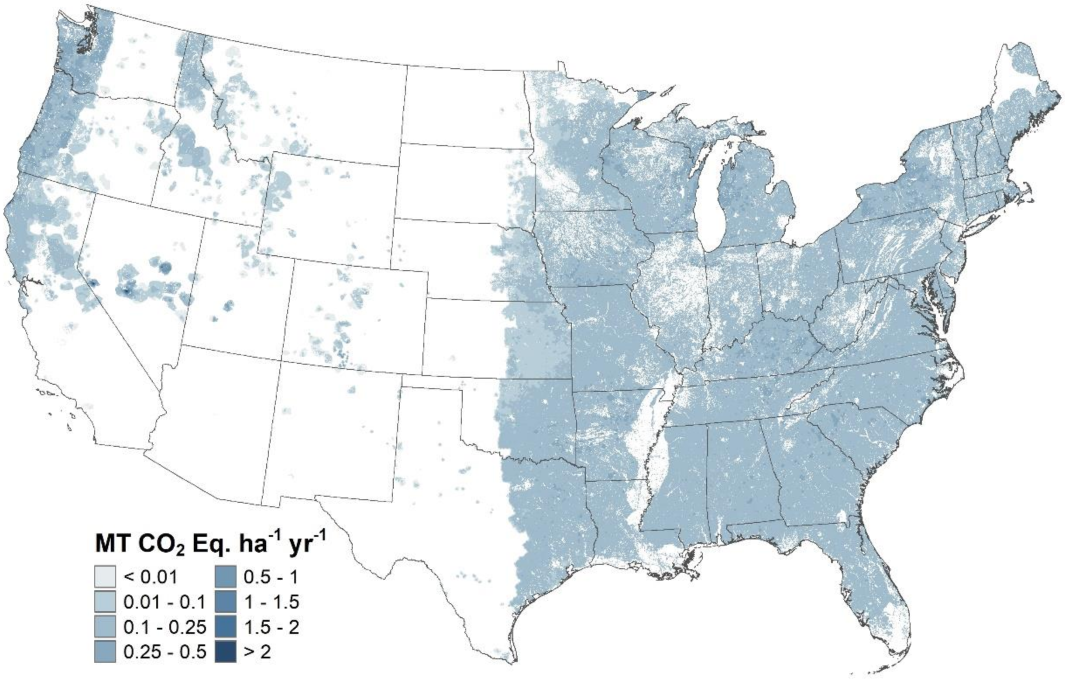
Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-9: Croplands, 2015 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Figure 5-10: Grasslands, 2015 Annual Indirect N_2O Emissions from Leaching and Runoff Using the Tier 3 DayCent Model



Note: Only national-scale emissions are estimated for 2016 to 2020 using a splicing method, and therefore the fine-scale emission patterns in this map are based on Inventory data from 2015.

Methodology and Time-Series Consistency

The *2006 IPCC Guidelines* (IPCC 2006) divide emissions from the agricultural soil management source category into five components, including (1) direct emissions from N additions to cropland and grassland mineral soils from synthetic fertilizers, biosolids (i.e., treated sewage sludge), crop residues (legume N-fixing and non-legume crops), and organic amendments; (2) direct emissions from soil organic matter mineralization due to land use and management change; (3) direct emissions from drainage of organic soils in croplands and grasslands; (4) direct emissions from soils due to manure deposited by livestock on PRP grasslands; and (5) indirect emissions from soils and water from N additions and manure deposition to soils that lead to volatilization, leaching, or runoff of N and subsequent conversion to N_2O.

In this source category, the United States reports on all croplands, as well as all managed grasslands, whereby anthropogenic greenhouse gas emissions are estimated consistent with the managed land concept (IPCC 2006), including direct and indirect N_2O emissions from asymbiotic fixation[16] and mineralization of N associated with decomposition of soil organic matter and residues. One recommendation from IPCC (2006) that has not been completely adopted is the estimation of emissions from grassland pasture renewal, which involves occasional plowing to improve forage production in pastures. Currently no data are available to address pasture renewal.

Direct N_2O Emissions

The methodology used to estimate direct N_2O emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches, along with application of a splicing method for latter

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[16] N inputs from asymbiotic N fixation are not directly addressed in *2006 IPCC Guidelines*, but are a component of the N inputs and total emissions from managed lands and are included in the Tier 3 approach developed for this source.

years in the Inventory time series (IPCC 2006; Del Grosso et al. 2010). A Tier 3 process-based model (DayCent) is used to estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010). The Tier 3 approach has been specifically designed and tested to estimate N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 5-3 for further elaboration). Moreover, the Tier 3 approach addresses direct N_2O emissions and soil C stock changes from mineral cropland soils in a single analysis. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is consistent activity data and treatment of the processes, and interactions are considered between C and N cycling in soils.

The Tier 3 approach is based on the crop and land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2018a). The NRI is a statistically-based sample of all non-federal land,[17] and includes 349,464 points on agricultural land for the conterminous United States that are included in the Tier 3 method. The Tier 1 approach is used to estimate the emissions from 175,527 locations in the NRI survey across the time series, which are designated as cropland or grassland (discussed later in this section). Each survey location is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with the same land-use/management history as the survey location). Each NRI survey location was sampled on a 5-year cycle from 1982 until 1997. For cropland, data were collected in 4 out of 5 years in the cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, which are currently available through 2015 (USDA-NRCS 2018a).

Box 5-3: Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC (2006) Tier 1 approach is based on multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on an input-by-input basis. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. In contrast, the Tier 3 approach developed for this Inventory is based on application of a process-based model (i.e., DayCent) that represents the interaction of N inputs, land use and management, as well as environmental conditions at specific locations, such as freeze-thaw effects that generate hot moments of N_2O emissions (Wagner-Riddle et al. 2017). Consequently, the Tier 3 approach accounts for land-use and management impacts and their interaction with environmental factors, such as weather patterns and soil characteristics, in a more comprehensive manner, which will enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more detailed activity data (e.g., crop-specific N fertilization rates), additional data inputs (e.g., daily weather, soil types), and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent, and thus it is critical to evaluate the output of Tier 3 methods against measured data in order to demonstrate that the method is an improvement over lower tier methods for estimating emissions (IPCC 2006). Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year and cannot be stored in soils and contribute to N_2O emissions in subsequent years. This is a simplifying assumption that may create bias in estimated N_2O emissions for a specific year. In contrast, the process-based model in the Tier 3 approach includes the legacy effect of N added to soils in previous years that is re-mineralized from soil organic matter and emitted as N_2O during subsequent years.

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[17] The NRI survey does include sample points on federal lands, but the program does not collect data from those sample locations.

DayCent is used to estimate N_2O emissions associated with production of alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, but is not applied to estimate N_2O emissions from other crops or rotations with other crops,[18] such as sugarcane, some vegetables, and perennial/horticultural crops. Areas that are converted between agriculture (i.e., cropland and grassland) and other land uses, such as forest land, wetland and settlements, are not simulated with DayCent. DayCent is also not used to estimate emissions from land areas with very gravelly, cobbly, or shaley soils in the topsoil (greater than 35 percent by volume in the top 30 cm of the soil profile), or to estimate emissions from drained organic soils (Histosols). The Tier 3 method has not been fully tested for estimating N_2O emissions associated with these crops and rotations, land uses, as well as organic soils or cobbly, gravelly, and shaley mineral soils. In addition, federal grassland areas are not simulated with DayCent due to limited activity data on land use histories. For areas that are not included in the DayCent simulations, Tier 1 methods are used to estimate emissions, including (1) direct emissions from N inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP N additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands.

A splicing method is used to estimate soil N_2O emissions from 2016 to 2020 at the national scale because new NRI activity data have not been incorporated into the analysis for those years. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions that are derived using the Tier 3 method. Surrogate data for these regression models includes corn and soybean yields from USDA-NASS statistics,[19] and weather data from the PRISM Climate Group (PRISM 2018). For the Tier 1 method, a linear-time series model is used to estimate emissions from 2016 to 2020 without surrogate data. See Box 5-4 for more information about the splicing method. Emission estimates for 2016 to 2020 will be recalculated in future Inventory reports when new NRI data are available.

Box 5-4: Surrogate Data Method

An approach to extend the time series is needed for Agricultural Soil Management because there are typically activity data gaps at the end of the time series. This is mainly because the NRI survey program, which provides critical information for estimating greenhouse gas emissions and removals, does not release data every year.

Splicing methods have been used to impute missing data at the end of the emission time series for both the Tier 1 and 3 methods. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate emissions based on the modeled 1990 to 2015 emissions data, which has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil nitrous oxide), Xβ for the Tier 3 method contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. The term Xβ for the Tier 1 method only contains year as a predictor of emission patterns over the time series (change in emissions per year), and therefore, is a linear time series model with no surrogate data. Parameters are estimated from the emissions data for 1990 to 2015 using standard statistical techniques, and these estimates are used in the model described above to predict the missing emissions data for 2016 to 2020.

A critical issue with splicing methods is to account for the additional uncertainty introduced by predicting emissions without compiling the full inventory. Specifically, uncertainty will increase for years with imputed

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[18] A small proportion of the major commodity crop production, such as corn and wheat, is included in the Tier 1 analysis because these crops are rotated with other crops or land uses (e.g., forest lands) that are not simulated by DayCent.

[19] See https://quickstats.nass.usda.gov/.

estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This additional uncertainty is quantified within the model framework using a Monte Carlo approach. Consequently, the uncertainty from the original inventory data is combined with the uncertainty in the data splicing model. The approach requires estimating parameters in the data splicing models in each Monte Carlo simulation for the full inventory (i.e., the surrogate data model is refit with the draws of parameters values that are selected in each Monte Carlo iteration, and used to produce estimates with inventory data from 1990 to 2015). Therefore, the data splicing method generates emissions estimates from each surrogate data model in the Monte Carlo analysis, which are used to derive confidence intervals in the estimates for the missing emissions data from 2016 to 2020. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach for Mineral Cropland Soils

The DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001 and 2011) is used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of a wide variety of crops (see list in previous section) based on the crop histories in the 2015 NRI (USDA-NRCS 2018a). Crops simulated by DayCent are grown on approximately 85 percent of total cropland area in the United States. The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1[20] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2018), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). DayCent is used to estimate direct N_2O emissions due to mineral N available from the following sources: (1) application of synthetic fertilizers; (2) application of livestock manure; (3) retention of crop residues in the field for N-fixing legumes and non-legume crops and subsequent mineralization of N during microbial decomposition (i.e., leaving residues in the field after harvest instead of burning or collecting residues); (4) mineralization of N from decomposition of soil organic matter; and (5) asymbiotic fixation.

Management activity data from several sources supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. These data are combined with other datasets in an imputation analysis that extend the time series from 1990 to 2015. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below), b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994), and c) assign management practices from the CEAP survey to specific NRI locations using predictive mean matching methods that are adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a very large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. The matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. There are six complete imputations of the management activity data using these methods.

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[20] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2015. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature, and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

To determine trends in mineral fertilization and manure amendments from 1979 to 2015, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2018). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both rates. This approach captures the relationship between mineral fertilization and manure amendment practices for U.S. croplands based directly on the observed patterns in the CEAP survey data.

To determine the trends in tillage management from 1979 to 2015, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and USDA-ERS Agriculture Resource Management Surveys (ARMS) data from 2002 to 2015 (Claasen et al. 2018). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). It is assumed that the majority of agricultural lands are managed with full tillage prior to 1985.

For cover crops, CEAP data are combined with information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

The IPCC method considers crop residue N and N mineralized from soil organic matter as activity data. However, they are not treated as activity data in DayCent simulations because residue production, symbiotic N fixation (e.g., legumes), mineralization of N from soil organic matter, and asymbiotic N fixation are internally generated by the model as part of the simulation. In other words, DayCent accounts for the influence of symbiotic N fixation, mineralization of N from soil organic matter and crop residue retained in the field, and asymbiotic N fixation on N_2O emissions, but these are not model inputs.

The N_2O emissions from crop residues are reduced by approximately 3 percent (the assumed average burned portion for crop residues in the United States) to avoid double counting associated with non-CO_2 greenhouse gas emissions from agricultural residue burning. Estimated levels of residue burning are based on state inventory data (ILENR 1993; Oregon Department of Energy 1995; Noller 1996; Wisconsin Department of Natural Resources 1993; Cibrowski 1996).

Uncertainty in the emission estimates from DayCent is associated with input uncertainty due to missing management data in the NRI survey that is imputed from other sources; model uncertainty due to incomplete specification of C and N dynamics in the DayCent model parameters and algorithms; and sampling uncertainty associated with the statistical design of the NRI survey. To assess input uncertainty, C and N dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator derived from fitting a linear mixed-effect model (Ogle et al. 2007; Del Grosso et al. 2010). Sampling uncertainty is assessed using NRI replicate sampling weights. These data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2015. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator), and random selection of a set of survey weights from the replicates associated with the NRI survey design.

Nitrous oxide emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2015 using the DayCent model. However, note that the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (See Section 6.1, Representation of the U.S. Land Base for more information). Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the DayCent model is applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the time series, 2016 to 2020, based on the pattern in emissions data from 1990 to 2015 (See Box 5-4). The pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). The time series will be updated with the Tier 3 method in the future as new activity data are incorporated into the analysis.

Nitrous oxide emissions from managed agricultural lands are the result of interactions among anthropogenic activities (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). It is not possible to partition N_2O emissions into each anthropogenic activity directly from model outputs due to the complexity of the interactions (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). To approximate emissions by activity, the amount of mineral N added to the soil, or made available through decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere, is determined for each N source and then divided by the total amount of mineral N in the soil according to the DayCent model simulation. The percentages are then multiplied by the total of direct N_2O emissions in order to approximate the portion attributed to N management practices. This approach is only an approximation because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case (Delgado et al. 2009). However, this approach allows for further disaggregation of emissions by source of N, which is valuable for reporting purposes and is analogous to the reporting associated with the IPCC (2006) Tier 1 method, in that it associates portions of the total soil N_2O emissions with individual sources of N.

Tier 1 Approach for Mineral Cropland Soils

The IPCC (2006) Tier 1 methodology is used to estimate direct N_2O emissions for mineral cropland soils that are not simulated by DayCent (e.g., DayCent has not been parametrized to simulate all crop types and some soil types such as *Histosols*). For the Tier 1 method, estimates of direct N_2O emissions from N applications are based on mineral soil N that is made available from the following practices: (1) the application of synthetic commercial fertilizers; (2) application of managed manure and non-manure commercial organic fertilizers; and (3) decomposition and mineralization of nitrogen from above- and below-ground crop residues in agricultural fields (i.e., crop biomass that is not harvested). Non-manure commercial organic amendments are only included in the Tier 1 analysis because these data are not available at the county-level, which is necessary for the DayCent simulations. Consequently, all commercial organic fertilizer, as well as manure that is not added to crops in the DayCent simulations, are included in the Tier 1 analysis. The following sources are used to derive activity data:

- A process-of-elimination approach is used to estimate synthetic N fertilizer additions for crop areas that are not simulated by DayCent. The total amount of fertilizer used on farms has been estimated at the county-level by the USGS using sales records from 1990 to 2012 (Brakebill and Gronberg 2017). For 2013 through 2016, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 2013 through 2021).[21] After subtracting the portion of fertilizer applied to crops and grasslands simulated by DayCent (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources), the remainder of the total fertilizer used on farms is assumed to be applied to crops that are not simulated by DayCent.
- Similarly, a process-of-elimination approach is used to estimate manure N additions for crops that are not simulated by DayCent. The total amount of manure available for land application to soils has been estimated with methods described in the Manure Management section (Section 5.2) and annex (Annex 3.11). The

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[21] The fertilizer consumption data in AAPFCO are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b).

amount of manure N applied in the Tier 3 approach to crops and grasslands is subtracted from total annual manure N available for land application (see Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections for information on data sources). This difference is assumed to be applied to crops that are not simulated by DayCent.

- Commercial organic fertilizer additions are based on organic fertilizer consumption statistics, which are converted from mass of fertilizer to units of N using average organic fertilizer N content, which range between 2.3 to 4.2 percent across the time series (TVA 1991 through 1994; AAPFCO 1995 through 2021). Commercial fertilizers do include dried manure and biosolids (i.e., treated sewage sludge), but the amounts are removed from the commercial fertilizer data to avoid double counting[22] with the manure N dataset described above and the biosolids (i.e., treated sewage sludge) amendment data discussed later in this section.
- Crop residue N is derived by combining amounts of above- and below-ground biomass, which are determined based on NRI crop area data (USDA-NRCS 2018a), crop production yield statistics (USDA-NASS 2019), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields from harvest (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006). N inputs from residue were reduced by 3 percent to account for average residue burning portions in the United States.

The total amount of soil mineral N from applied fertilizers and crop residues is multiplied by the IPCC (2006) default emission factor to derive an estimate of direct N_2O emissions using the Tier 1 method. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 1 methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions from 2016 to 2020 based on the emission patterns between 1990 and 2015 (See Box 5-4), with the exception of crop residue N, in which the data splicing method is only used for 2019 and 2020. The emission pattern is determined using a linear regression model with moving-average (ARMA) errors. Linear extrapolation is a standard data splicing method for approximating missing values at the end of an inventory time series (IPCC 2006). As with the Tier 3 method, the time series that is based on the splicing methods will be recalculated in a future Inventory report with updated activity data.

Tier 1 and 3 Approaches for Direct N_2O Emissions from Mineral Grassland Soils

As with N_2O emissions from croplands, the Tier 3 process-based DayCent model and Tier 1 method described in IPCC (2006) are combined to estimate emissions from non-federal grasslands and PRP manure N additions for federal grasslands, respectively. Grassland includes pasture and rangeland that produce grass or mixed grass/legume forage primarily for livestock grazing. Rangelands are extensive areas of native grassland that are not intensively managed, while pastures are seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation, fertilization, or inter-seeding legumes. DayCent is used to simulate N_2O emissions from NRI survey locations (USDA-NRCS 2018a) on non-federal grasslands resulting from manure deposited by livestock directly onto pastures and rangelands (i.e., PRP manure), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure such as Daily Spread or manure collected from other animal waste management systems such as lagoons and digesters), and synthetic fertilizer application. Other N inputs are simulated within the DayCent framework, including N input from mineralization due to decomposition of soil organic matter and N inputs from senesced grass litter, as well as asymbiotic fixation of N from the atmosphere. The simulations used the same weather, soil, and synthetic N fertilizer data as discussed under the Tier 3 Approach in the Mineral Cropland Soils section. Mineral N fertilization rates are based on data from the Carbon Sequestration Rural Appraisals (CSRA) conducted by the USDA-NRCS (USDA-NRCS, unpublished data). The CSRA was a solicitation of expert knowledge from USDA-NRCS staff throughout the United States to

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[22] Commercial organic fertilizers include dried blood, tankage, compost, and other, but the dried manure and biosolids (i.e., treated sewage sludge) are also included in other datasets in this Inventory. Consequently, the proportions of dried manure and biosolids, which are provided in the reports (TVA 1991 through 1994; AAPFCO 1995 through 2021), are used to estimate the N amounts in dried manure and biosolids. To avoid double counting, the resulting N amounts for dried manure and biosolids are subtracted from the total N in commercial organic fertilizers before estimating emissions using the Tier 1 method.

support the Inventory. Biological N fixation is simulated within DayCent, and therefore is not an input to the model.

Manure N deposition from grazing animals in PRP systems (i.e., PRP manure N) is a key input of N to grasslands. The amounts of PRP manure N applied on non-federal grasslands for each NRI survey location are based on the amount of N excreted by livestock in PRP systems that is estimated in the Manure Management section (See Section 5.2 and Annex 3.11). The total amount of N excreted in each county is divided by the grassland area to estimate the N input rate associated with PRP manure. The resulting rates are a direct input into the DayCent simulations. The N input is subdivided between urine and dung based on a 50:50 split. DayCent simulations of non-federal grasslands accounted for approximately 61 percent of total PRP manure N in aggregate across the country.[23] The remainder of the PRP manure N in each state is assumed to be excreted on federal grasslands, and the N_2O emissions are estimated using the IPCC (2006) Tier 1 method.

Biosolids (i.e., treated sewage sludge) are assumed to be applied on grasslands. Application of biosolids is estimated from data compiled by EPA (1993, 1999, 2003), McFarland (2001), and NEBRA (2007) (see Section 7.2 Wastewater Treatment for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Biosolids data are only available at the national scale, and it is not possible to associate application with specific soil conditions and weather at NRI survey locations. Therefore, DayCent could not be used to simulate the influence of biosolids on N_2O emissions from grassland soils, and consequently, emissions from biosolids are estimated using the IPCC (2006) Tier 1 method.

Soil N_2O emission estimates from DayCent are adjusted using a structural uncertainty estimator accounting for uncertainty in model algorithms and parameter values (Del Grosso et al. 2010). There is also sampling uncertainty for the NRI survey that is propagated through the estimate with replicate sampling weights associated with the survey. N_2O emissions for the PRP manure N deposited on federal grasslands and applied biosolids N are estimated using the Tier 1 method by multiplying the N input by the default emission factor. Emissions from manure N are estimated at the state level and aggregated to the entire country, but emissions from biosolids N are calculated exclusively at the national scale. Further elaboration on the methodology and data used to estimate N_2O emissions from mineral soils are described in Annex 3.12.

Soil N_2O emissions and 95 percent confidence intervals are estimated for each year between 1990 and 2015 based on the Tier 1 and 3 methods, with the exception of biosolids (discussed below). In order to ensure time-series consistency, emissions from 2016 to 2020 are estimated using a splicing method as described in Box 5-4, with a linear extrapolation based on the emission patterns in the 1990 to 2015 data. Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with croplands, estimates for 2016 to 2020 will be recalculated in a future Inventory when the activity data are updated. Biosolids application data are compiled through 2020 in this Inventory, and therefore soil N_2O emissions and confidence intervals are estimated using the Tier 1 method for all years in the time series without application of the splicing method.

Tier 1 Approach for Drainage of Organic Soils in Croplands and Grasslands

The IPCC (2006) Tier 1 method is used to estimate direct N_2O emissions due to drainage of organic soils in croplands and grasslands at a state scale. State-scale estimates of the total area of drained organic soils are obtained from the 2015 NRI (USDA-NRCS 2018a) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). Temperature data from the PRISM Climate Group (PRISM 2018) are used to subdivide areas into temperate and tropical climates according to the climate classification from IPCC (2006). To estimate annual emissions, the total temperate area is multiplied by the IPCC default emission factor for temperate regions, and the total tropical area is multiplied by the IPCC default emission factor for tropical regions (IPCC 2006). Annual NRI data are only available between 1990 and 2015, but the time series was adjusted using data from the Forest Inventory and Analysis Program (USFS 2019) in order to estimate emissions from 2016 to

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[23] A small amount of PRP N (less than 1 percent) is deposited in grazed pasture that is in rotation with annual crops, and is reported in the grassland N_2O emissions.

2018. The land representation data have not been updated for this Inventory, so the amount of drained organic soils is assumed to be the same in 2019 and 2020 as the estimated areas in 2018, and consequently the emissions in 2019 and 2020 are also assumed to be the same as 2018. Further elaboration on the methodology and data used to estimate N_2O emissions from organic soils are described in Annex 3.12.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from the Tier 1 and 3 approaches for mineral and drained organic soils occurring in both croplands and grasslands are summed to obtain the total direct N_2O emissions from agricultural soil management (see Table 5-15 and Table 5-16).

Indirect N_2O Emissions Associated with Nitrogen Management in Cropland and Grasslands

Indirect N_2O emissions occur when mineral N applied or made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer, organic amendments (e.g., manure, biosolids), and deposition of PRP manure. Nitrogen made available from mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and input of N from asymbiotic fixation also contributes to volatilized N emissions. Volatilized N can be returned to soils through atmospheric deposition, and a portion of the deposited N is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of NO_3^-) that is made available through anthropogenic activity on managed lands, mineralization of soil organic matter and residue, including N incorporated into crops and forage from symbiotic N fixation, and inputs of N into the soil from asymbiotic fixation. The NO_3^- is subject to denitrification in water bodies, which leads to N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands and grasslands.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Atmospheric Deposition of Volatilized N

The Tier 3 DayCent model and IPCC (2006) Tier 1 methods are combined to estimate the amount of N that is volatilized and eventually emitted as N_2O. DayCent is used to estimate N volatilization for land areas whose direct emissions are simulated with DayCent (i.e., most commodity and some specialty crops and most grasslands). The N inputs included are the same as described for direct N_2O emissions in the Tier 3 Approach for Mineral Cropland Soils and Direct N_2O Emissions from Grassland Soils sections. Nitrogen volatilization from all other areas is estimated using the Tier 1 method with default IPCC fractions for N subject to volatilization (i.e., N inputs on croplands not simulated by DayCent, PRP manure N excreted on federal grasslands, and biosolids [i.e., treated sewage sludge] application on grasslands).

The IPCC (2006) default emission factor is multiplied by the amount of volatilized N generated from both DayCent and Tier 1 methods to estimate indirect N_2O emissions occurring following re-deposition of the volatilized N (see Table 5-18). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

Tier 1 and 3 Approaches for Indirect N_2O Emissions from Leaching/Runoff

As with the calculations of indirect emissions from volatilized N, the Tier 3 DayCent model and IPCC (2006) Tier 1 method are combined to estimate the amount of N that is subject to leaching and surface runoff into water bodies, and eventually emitted as N_2O. DayCent is used to simulate the amount of N transported from lands in the Tier 3 Approach. Nitrogen transport from all other areas is estimated using the Tier 1 method and the IPCC (2006) default factor for the proportion of N subject to leaching and runoff associated with N applications on croplands that are not simulated by DayCent, applications of biosolids on grasslands, and PRP manure N excreted on federal grasslands.

For both the DayCent Tier 3 and IPCC (2006) Tier 1 methods, nitrate leaching is assumed to be an insignificant source of indirect N_2O in cropland and grassland systems in arid regions, as discussed in IPCC (2006). In the United States, the threshold for significant nitrate leaching is based on the potential evapotranspiration (PET) and rainfall amount, similar to IPCC (2006), and is assumed to be negligible in regions where the amount of precipitation does not exceed 80 percent of PET (Note: All irrigated systems are assumed to have significant amounts of leaching of N even in drier climates).

For leaching and runoff data estimated by the Tier 3 and Tier 1 approaches, the IPCC (2006) default emission factor is used to estimate indirect N_2O emissions that occur in groundwater and waterways (see Table 5-18). Further elaboration on the methodology and data used to estimate indirect N_2O emissions are described in Annex 3.12.

In order to ensure time-series consistency, indirect soil N_2O emissions are estimated using the Tier 1 and 3 approaches from 1990 to 2015 and then a linear extrapolation data splicing method, described in Box 5-4, is applied to estimate emissions from 2016 to 2020 based on the emission patterns from 1990 to 2015. Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the direct N_2O emissions, the time series will be recalculated in a future Inventory report when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is estimated for each of the following five components of N_2O emissions from agricultural soil management: (1) direct emissions simulated by DayCent; (2) the components of indirect emissions (N volatilized and leached or runoff) simulated by DayCent; (3) direct emissions estimated with the IPCC (2006) Tier 1 method; (4) the components of indirect emissions (N volatilized and leached or runoff) estimated with the IPCC (2006) Tier 1 method; and (5) indirect emissions estimated with the IPCC (2006) Tier 1 method. Uncertainty in direct emissions as well as the components of indirect emissions that are estimated from DayCent are derived from a Monte Carlo Analysis (consistent with IPCC Approach 2), addressing uncertainties in model inputs and structure (i.e., algorithms and parameterization) (Del Grosso et al. 2010). For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the splicing method (See Box 5-4).

Simple error propagation methods (IPCC 2006) are used to derive confidence intervals for direct emissions estimated with the IPCC (2006) Tier 1 method, the proportion of volatilization and leaching or runoff estimated with the IPCC (2006) Tier 1 method, and indirect N_2O emissions. Uncertainty in the splicing method is also included in the error propagation for 2016 to 2020 (see Box 5-4). Additional details on the uncertainty methods are provided in Annex 3.12.

Table 5-19 shows the combined uncertainty for direct soil N_2O emissions. The estimated emissions ranges from 33 percent below to 33 percent above the 2020 emission estimate of 271.7 MMT CO_2 Eq. The combined uncertainty for indirect soil N_2O emissions ranges from 67 percent below to 145 percent above the 2020 estimate of 44.6 MMT CO_2 Eq.

Table 5-19: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2020 (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	271.7	183.2	360.2	-33%	33%
Indirect Soil N_2O Emissions	N_2O	44.6	14.9	109.0	-67%	145%

Note: Due to lack of data, uncertainties in PRP manure N production, other organic fertilizer amendments, and biosolids (i.e., treated sewage sludge) amendments to soils are currently treated as certain; these sources of

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uncertainty will be included in future Inventory reports, which is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006).

Additional uncertainty is associated with an incomplete estimation of N_2O emissions from managed croplands and grasslands in Hawaii and Alaska. The Inventory currently includes the N_2O emissions from managed manure and PRP N additions in Alaska and Hawaii, and drained organic soils in Hawaii. Land areas used for agriculture in Alaska and Hawaii are small relative to major crop commodity states in the conterminous United States, so the emissions are likely to be small for the other sources of N (e.g., synthetic fertilizer and crop residue inputs), which are not currently included in the Inventory.

QA/QC and Verification

General (Tier 1) and category-specific (Tier 2) QA/QC activities were conducted consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. DayCent results for N_2O emissions and NO_3^- leaching are compared with field data representing various cropland and grassland systems, soil types, and climate patterns (Del Grosso et al. 2005; Del Grosso et al. 2008), and further evaluated by comparing the model results to emission estimates produced using the IPCC (2006) Tier 1 method for the same sites. Nitrous oxide measurement data for cropland are available for 64 sites representing 796 different combinations of fertilizer treatments and cultivation practices, and measurement data for grassland are available for 13 sites representing 36 different management treatments. Nitrate leaching data are available for 12 sites, representing 279 different combinations of fertilizer treatments and tillage practices. In general, DayCent predicted N_2O emission and nitrate leaching for these sites reasonably well. See Annex 3.12 for more detailed information about the comparisons.

Databases containing input data and probability distribution functions required for DayCent simulations of croplands and grasslands and unit conversion factors have been checked, in addition to the program scripts that are used to run the Monte Carlo uncertainty analysis. Small input errors were found in the amount of synthetic and managed manure N applied to soils in the Tier 3 model simulations. Corrections were made by adjusting the amount of N applied to the maximum available by state and N_2O emissions were reduced based on the latest N Fertilizer sales data and managed manure N available for application to soils. Databases containing input data, emission factors, and calculations required for the Tier 1 method have been checked and updated as needed. In particular, the amount of synthetic and managed manure N included in the Tier 1 analysis was also adjusted in this process so that the total synthetic and managed manure N was equal to the amounts reported by the activity data sources. Links between spreadsheets have also been checked, updated, and corrected when necessary.

Recalculations Discussion

Three improvements have been implemented in this Inventory leading to the need for recalculations. Updated synthetic N fertilizer sales data were available for 2015 and new sales data for 2016 were published, both incorporated into Tier 3 and Tier 1 analyses (AAPFCO 2021). Additionally, updates to the time series of PRP N and manure N available for application to soils were incorporated into the analysis. The surrogate data method was also applied to re-estimate N_2O emissions from N fertilizer applications for 2016 to 2020. Finally, errors in the previous Inventory were corrected where the amount of synthetic fertilizer or managed manure N were over-applied in the Tier 3 analysis resulting in more N than was available for application. These changes resulted in an average increase in emissions of 0.2 percent from 1990 to 2019 relative to the previous Inventory.

Planned Improvements

A key improvement for a future Inventory will be to incorporate additional management activity data from the USDA-NRCS Conservation Effects Assessment Project survey. This survey has compiled new data in recent years that will be available for the Inventory analysis by next year. The latest land use data will also be incorporated from the USDA National Resources Inventory and related management data from USDA-ERS ARMS surveys.

Several planned improvements are underway associated with improving the DayCent biogeochemical model. These improvements include a better representation of plant phenology, particularly senescence events following grain filling in crops. In addition, crop parameters associated with temperature and water stress effects on plant production will be further improved in DayCent with additional model calibration. Model development is underway to represent the influence of enhanced efficiency fertilizers, which include stabilized fertilizers (e.g., nitrification inhibitors and urease inhibitors), slow-release fertilizers (e.g., methylene urea or sulfur coated urea), and controlled release fertilizers (e.g., polymer-coated fertilizers), on N_2O emissions. Experimental study sites will continue to be added for quantifying model structural uncertainty. Studies that have continuous (daily) measurements of N_2O (e.g., Scheer et al. 2013) will be given priority. Other suggested improvements identified through public review are being evaluated for future Inventory submissions.

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that is used in the Field Burning of Agricultural Residues source category (see section 5.5). Alaska and Hawaii are not included for all sources in the current Inventory for agricultural soil management, with the exception of N_2O emissions from drained organic soils in croplands and grasslands for Hawaii, managed manure N and PRP N additions for grasslands in Alaska and Hawaii. There is also an improvement based on updating the Tier 1 emission factor for N_2O emissions from drained organic soils by using the revised factor in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013).

In addition, there is a planned improvement associated with implementation of the Tier 1 method. Specifically, soil N_2O emissions will be estimated and reported for N mineralization from soil organic matter decomposition that is accelerated with Forest Land Converted to Cropland and Grassland Converted to Cropland. A review of available data on biosolids (i.e., treated sewage sludge) application will also be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

These improvements are expected to be completed for the next Inventory (i.e., 2023 submission to the UNFCCC, 1990 through 2021 Inventory). However, the timeline may be extended if there are insufficient resources to fund all or part of these planned improvements.

5.5 Liming (CRF Source Category 3G)

Crushed limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are added to soils by land managers to increase soil pH (i.e., to reduce acidification). Carbon dioxide emissions occur as these compounds react with hydrogen ions in soils. The rate of degradation of applied limestone and dolomite depends on the soil conditions, soil type, climate regime, and whether limestone or dolomite is applied. Emissions from limestone and dolomite that are used in industrial processes (e.g., cement production, glass production, etc.) are reported in the IPPU chapter. Emissions from liming of soils have fluctuated between 1990 and 2020 in the United States, ranging from 2.2 MMT CO_2 Eq. to 6.0 MMT CO_2 Eq. across the entire time series. In 2020, liming of soils in the United States resulted in emissions of 2.4 MMT CO_2 Eq. (0.6 MMT C), representing a 49 percent decrease in emissions since 1990 (see Table 5-20 and Table 5-21). The trend is driven by variation in the amount of limestone and dolomite applied to soils over the time period.

Table 5-20: Emissions from Liming (MMT CO_2 Eq.)

Source	1990		2005		2016	2017	2018	2019	2020
Limestone	4.1		3.9		2.8	2.9	2.0	2.2	2.2
Dolomite	0.6		0.4		0.3	0.2	0.2	0.2	0.2
Total	**4.7**		**4.3**		**3.1**	**3.1**	**2.2**	**2.4**	**2.4**

Note: Totals may not sum due to independent rounding.

Table 5-21: Emissions from Liming (MMT C)

Source	1990		2005		2016	2017	2018	2019	2020
Limestone	1.1		1.1		0.8	0.8	0.6	0.6	0.6
Dolomite	0.2		0.1		0.1	0.1	0.1	0.1	0.1
Total	**1.3**		**1.2**		**0.8**	**0.8**	**0.6**	**0.7**	**0.6**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using a Tier 2 methodology consistent with IPCC (2006). The annual amounts of limestone and dolomite, which are applied to soils (see Table 5-22), were multiplied by CO_2 emission factors from West and McBride (2005). These country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than the IPCC default emission factors because they account for the portion of carbonates that are transported from soils through hydrological processes and eventually deposited in ocean basins (West and McBride 2005). This analysis of lime dissolution is based on studies in the Mississippi River basin, where the vast majority of lime application occurs in the United States (West 2008). Moreover, much of the remaining lime application is occurring under similar precipitation regimes, and so the emission factors are considered a reasonable approximation for all lime application in the United States (West 2008) (See Box 5-5).

The annual application rates of limestone and dolomite were derived from estimates and industry statistics provided in the U.S. Geological Survey (USGS) *Minerals Yearbook* (Tepordei 1993 through 2006; Willett 2007a, 2007b, 2009, 2010, 2011a, 2011b, 2013a, 2014, 2015, 2016, 2017, 2020a), as well as preliminary data that will eventually be published in the *Minerals Yearbook* for the latter part of the time series (Willett 2019, 2020b, 2021a, 2021b). Data for the final year of the inventory is based on the *Mineral Industry Surveys*, as discussed below (USGS 2021). The U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) compiled production and use information through surveys of crushed stone manufacturers. However, manufacturers provided different levels of detail in survey responses so the estimates of total crushed limestone and dolomite production and use were divided into three components: (1) production by end-use, as reported by manufacturers (i.e., “specified” production); (2) production reported by manufacturers without end-uses specified (i.e., “unspecified” production); and (3) estimated additional production by manufacturers who did not respond to the survey (i.e., “estimated” production).

Box 5-5: Comparison of the Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from liming of soils were estimated using a Tier 2 methodology based on emission factors specific to the United States that are lower than the IPCC (2006) default emission factors. Most lime application in the United States occurs in the Mississippi River basin, or in areas that have similar soil and rainfall regimes as the Mississippi River basin. Under these conditions, a significant portion of dissolved agricultural lime leaches through the soil into groundwater. Groundwater moves into channels and is transported to larger rives and eventually the ocean where $CaCO_3$ precipitates to the ocean floor (West and McBride 2005). The U.S.-specific emission factors (0.059 metric ton C/metric ton limestone and 0.064 metric ton C/metric ton dolomite) are about half of the IPCC (2006) emission factors (0.12 metric ton C/metric ton limestone and 0.13 metric ton C/metric ton dolomite). For comparison, the 2020 U.S. emission estimate from liming of soils is 2.4 MMT CO_2 Eq. using the country-specific factors. In contrast, emissions would be estimated at 4.8 MMT CO_2 Eq. using the IPCC (2006) default emission factors.

Data on “specified” limestone and dolomite amounts were used directly in the emission calculation because the end use is provided by the manufacturers and can be used to directly determine the amount applied to soils. However, it is not possible to determine directly how much of the limestone and dolomite is applied to soils for manufacturer surveys in the “unspecified” and “estimated” categories. For these categories, the amounts of crushed limestone and dolomite applied to soils were determined by multiplying the percentage of total "specified" limestone and dolomite production that is applied to soils, by the total amounts of "unspecified" and "estimated" limestone and dolomite production. In other words, the proportion of total "unspecified" and "estimated" crushed limestone and dolomite that was applied to soils is proportional to the amount of total "specified" crushed limestone and dolomite that was applied to soils.

In addition, data were not available for 1990, 1992, 2019, and 2020 on the fractions of total crushed stone production that were limestone and dolomite, and on the fractions of limestone and dolomite production that were applied to soils. To estimate the 1990 and 1992 data, a set of average fractions were calculated using the 1991 and 1993 data. These average fractions were applied to the quantity of "total crushed stone produced or used" reported for 1990 and 1992 in the 1994 *Minerals Yearbook* (Tepordei 1996). To estimate 2019 and 2020 data, 2018 and 2019 fractions were applied to the 2019 and 2020 estimates of total crushed stone, respectively. The basis for these estimates is from the USGS *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Fourth Quarter of 2020 and First Quarter of 2021* (USGS 2020; USGS 2021).

The primary source for limestone and dolomite activity data is the *Minerals Yearbook*, published by the Bureau of Mines through 1996 and by the USGS from 1997 to the present. In 1994, the "Crushed Stone" chapter in the *Minerals Yearbook* began rounding (to the nearest thousand metric tons) quantities for total crushed stone produced or used. It then reported revised (rounded) quantities for each of the years from 1990 to 1993. In order to minimize the inconsistencies in the activity data, these revised production numbers have been used in all of the subsequent calculations.

Table 5-22: Applied Minerals (MMT)

Mineral	1990	2005	2016	2017	2018	2019	2020
Limestone	19.0	18.1	13.0	13.4	9.4	10.1	9.9
Dolomite	2.4	1.9	1.1	0.8	0.9	1.0	1.0

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2019. In addition, the same methods are applied throughout the time series, and the activity data are extended in the last two years of the time series based on proportions of specified, unspecified and estimated agricultural limestone and dolomite so that estimates are consistent with the previous year's data. These years will be recalculated when additional data are available on the amounts of limestone and dolomite that are used for agricultural purposes.

Uncertainty

Uncertainty regarding the amount of limestone and dolomite applied to soils was estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b). Analysis of the uncertainty associated with the emission factors included the fraction of lime dissolved by nitric acid versus the fraction that reacts with carbonic acid, and the portion of bicarbonate that leaches through the soil and is transported to the ocean. Uncertainty regarding the time associated with leaching and transport was not addressed in this analysis, but is assumed to be a relatively small contributor to the overall uncertainty (West 2005). The probability distribution functions for the fraction of lime dissolved by nitric acid and the portion of bicarbonate that leaches through the soil were represented as triangular distributions between ranges of zero and 100 percent of the estimates. The uncertainty surrounding these two components largely drives the overall uncertainty.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty in CO_2 emissions from liming. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 5-23. Carbon dioxide emissions from carbonate lime application to soils in 2020 were estimated to be between -0.26 and 4.73 MMT CO_2 Eq. at the 95 percent confidence level. This confidence interval represents a range of 111 percent below to 97 percent above the 2020 emission estimate of 2.4 MMT CO_2 Eq. Note that there is a small probability of a negative emissions value leading to a net uptake of CO_2 from the atmosphere. Net uptake occurs due to the dominance of the carbonate lime dissolving in carbonic acid rather than nitric acid (West and McBride 2005).

Table 5-23: Approach 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Liming (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Liming	CO_2	2.4	(0.26)	4.73	-111%	97%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for liming has been developed and implemented, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The quality control effort focused on the Tier 1 procedures for this Inventory. A small error was found in results for Florida and Georgia due to incorrect cell references in the spreadsheet, which was corrected. No other errors were found.

Recalculations Discussion

Limestone and dolomite application data for 2019 were updated with the recently acquired data from Willett, J.C. (2021a), rather than approximated by a ratio method, which was used in the previous Inventory. There were also corrections in cell references for Florida and Georgia. With these revisions, the emissions decreased by 1.2 percent for 2019 relative to the previous Inventory.

5.6 Urea Fertilization (CRF Source Category 3H)

The use of urea ($CO(NH_2)_2$) as a fertilizer leads to greenhouse gas emissions through the release of CO_2 that was fixed during the production of urea. In the presence of water and urease enzymes, urea that is applied to soils as fertilizer is converted into ammonium (NH_4^+), hydroxyl ion (OH), and bicarbonate (HCO_3^-). The bicarbonate then evolves into CO_2 and water. Emissions from urea fertilization in the United States were 5.3 MMT CO_2 Eq. (1.5 MMT C) in 2020 (Table 5-24 and Table 5-25). Carbon dioxide emissions have increased by 118 percent between 1990 and 2020 due to an increasing amount of urea that is applied to soils. The variation in emissions across the time series is driven by differences in the amounts of fertilizer applied to soils each year. Carbon dioxide emissions associated with urea that is used for non-agricultural purposes are reported in the IPPU chapter (Section 4.6).

Table 5-24: CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Urea Fertilization	2.4	3.5	4.7	4.9	5.0	5.1	5.3

Table 5-25: CO_2 Emissions from Urea Fertilization (MMT C)

Source	1990	2005	2016	2017	2018	2019	2020
Urea Fertilization	0.7	1.0	1.3	1.3	1.4	1.4	1.4

Methodology and Time-Series Consistency

Carbon dioxide emissions from the application of urea to agricultural soils were estimated using the IPCC (2006) Tier 1 methodology. The method assumes that C in the urea is released after application to soils and converted to CO_2. The annual amounts of urea applied to croplands (see Table 5-26) were derived from the state-level fertilizer sales data provided in *Commercial Fertilizer* reports (TVA 1991, 1992, 1993, 1994; AAPFCO 1995 through 2021).[24] These amounts were multiplied by the default IPCC (2006) emission factor (0.20 metric tons of C per metric ton of urea), which is equal to the C content of urea on an atomic weight basis. The calculations were made using a Monte Carlo analysis as described in the Uncertainty section below.

Fertilizer sales data are reported in fertilizer years (July previous year through June current year) so a calculation was performed to convert the data to calendar years (January through December). According to monthly fertilizer use data (TVA 1992b), 35 percent of total fertilizer used in any fertilizer year is applied between July and December of the previous calendar year, and 65 percent is applied between January and June of the current calendar year.

Fertilizer sales data for the 2017 through 2020 fertilizer years were not available for this Inventory. Therefore, urea application in the 2017 through 2020 fertilizer years were estimated using a linear, least squares trend of consumption over the data from the previous five years (2012 through 2016) at the state scale. A trend of five years was chosen as opposed to a longer trend as it best captures the current inter-state and inter-annual variability in consumption. State-level estimates of CO_2 emissions from the application of urea to agricultural soils were summed to estimate total emissions for the entire United States. The fertilizer year data is then converted into calendar year (Table 5-26) data using the method described above.

Table 5-26: Applied Urea (MMT)

	1990	2005	2016	2017	2018	2019	2020
Urea Fertilizer[a]	3.3	4.8	6.4	6.7	6.8	7.0	7.2

[a] These numbers represent amounts applied to all agricultural land, including *Cropland Remaining Cropland*, Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Settlements Remaining Settlements,* Land Converted to Settlements, *Forest Land Remaining Forest Land* and *Land Converted to Forest Land,* as it is not currently possible to apportion the data by land-use category.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. In addition, the same methods are applied in all years and the activity data are extended using a data splicing method with a linear extrapolation based on the last four years of urea fertilization data to ensure consistency in the time series. These years will be recalculated when additional data are available on urea fertilization.

Uncertainty

An Approach 2 Monte Carlo analysis is conducted as described by the IPCC (2006). The largest source of uncertainty is the default emission factor, which assumes that 100 percent of the C in $CO(NH_2)_2$ applied to soils is emitted as CO_2. The uncertainty surrounding this factor incorporates the possibility that some of the C may not be emitted to the atmosphere, and therefore the uncertainty range is set from 50 percent emissions to the maximum emission value of 100 percent using a triangular distribution. In addition, urea consumption data have uncertainty that is represented as a normal density. Due to the highly skewed distribution of the resulting emissions from the Monte Carlo uncertainty analysis, the estimated emissions are based on the analytical solution to the equation, and the confidence interval is approximated based on the values at 2.5 and 97.5 percentiles.

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[24] The amount of urea consumed for non-agricultural purposes in the United States is reported in the Industrial Processes and Product Use chapter, Section 4.6 Urea Consumption for Non-Agricultural Purposes.

Carbon dioxide emissions from urea fertilization of agricultural soils in 2020 are estimated to be between 3.02 and 5.44 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 43 percent below to 3 percent above the 2020 emission estimate of 5.3 MMT CO_2 Eq. (Table 5-27).

Table 5-27: Quantitative Uncertainty Estimates for CO_2 Emissions from Urea Fertilization (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Urea Fertilization	CO_2	5.3	3.02	5.44	-43%	+3%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

There are additional uncertainties that are not quantified in this analysis. There is uncertainty surrounding the assumptions underlying conversion of fertilizer years to calendar years. These uncertainties are negligible over multiple years because an over- or under-estimated value in one calendar year is addressed with a corresponding increase or decrease in the value for the subsequent year. In addition, there is uncertainty regarding the fate of C in urea that is incorporated into solutions of urea ammonium nitrate (UAN) fertilizer. Emissions of CO_2 from UAN applications to soils are not estimated in the current Inventory (see Planned Improvements).

QA/QC and Verification

A source-specific QA/QC plan for Urea Fertilization has been developed and implemented, consistent with the U.S. Inventory QA/QC plan. The UNFCCC expert review recommended using the analytical solution from the Tier 1 method for the estimate of CO_2 emissions from Urea Fertilization. This recommendation has been adopted for inventory reporting.

Recalculations Discussion

In the previous inventory, an error existed with the formula for predicting the total urea fertilizer consumption data for 2019. The error was corrected. New fertilization data were available for 2016, which was updated, and this also led to an update in the linear extrapolation from 2017 to 2020 (AAPFCO 2021). These modifications resulted in changes ranging from -4.1 percent and -0.1 percent for 2014 to 2019.

Planned Improvements

A key planned improvement is to incorporate Urea Ammonium Nitrate (UAN) in the estimation of Urea CO_2 emissions. Activity data for UAN have been identified, but additional information is needed to fully incorporate this type of fertilizer into the analysis, which will be completed in a future Inventory.

5.7 Field Burning of Agricultural Residues (CRF Source Category 3F)

Crop production creates large quantities of agricultural crop residues, which farmers manage in a variety of ways. For example, crop residues can be left in the field and possibly incorporated into the soil with tillage; collected and used as fuel, animal bedding material, supplemental animal feed, or construction material; composted and applied to soils; transported to landfills; or burned in the field. Field burning of crop residues is not considered a net source of CO_2 emissions because the C released to the atmosphere as CO_2 during burning is reabsorbed during the next growing season by the crop. However, crop residue burning is a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

In the United States, field burning of agricultural residues commonly occurs in southeastern states, the Great Plains, and the Pacific Northwest (McCarty 2011). The primary crops that are managed with residue burning include corn, cotton, lentils, rice, soybeans, sugarcane and wheat (McCarty 2009). In 2020, CH_4 and N_2O emissions from field burning of agricultural residues were 0.4 MMT CO_2 Eq. (17 kt) and 0.2 MMT CO_2 Eq. (1 kt), respectively (Table 5-28 and Table 5-29). Annual emissions of CH_4 and N_2O have increased from 1990 to 2020 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some of the crop types.

Table 5-28: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq.)

Gas/Crop Type	1990		2005		2016	2017	2018	2019	2020
CH_4	**0.4**		**0.4**		**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Maize	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Rice	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Wheat	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Barley	+		+		+	+	+	+	+
Oats	+		+		+	+	+	+	+
Other Small Grains	+		+		+	+	+	+	+
Sorghum	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Grass Hay	+		+		+	+	+	+	+
Legume Hay	+		+		+	+	+	+	+
Peas	+		+		+	+	+	+	+
Sunflower	+		+		+	+	+	+	+
Tobacco	+		+		+	+	+	+	+
Vegetables	+		+		+	+	+	+	+
Chickpeas	+		+		+	+	+	+	+
Dry Beans	+		+		+	+	+	+	+
Lentils	+		+		+	+	+	+	+
Peanuts	+		+		+	+	+	+	+
Soybeans	+		+		+	+	+	+	+
Potatoes	+		+		+	+	+	+	+
Sugarbeets	+		+		+	+	+	+	+
N_2O	**0.2**		**0.2**		**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Maize	+		+		0.1	0.1	0.1	0.1	0.1
Rice	+		+		+	+	+	+	+
Wheat	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Barley	+		+		+	+	+	+	+
Oats	+		+		+	+	+	+	+
Other Small Grains	+		+		+	+	+	+	+
Sorghum	+		+		+	+	+	+	+
Cotton	+		+		+	+	+	+	+
Grass Hay	+		+		+	+	+	+	+
Legume Hay	+		+		+	+	+	+	+
Peas	+		+		+	+	+	+	+

Sunflower	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
Total	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 5-29: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (kt)

Gas/Crop Type	1990	2005	2016	2017	2018	2019	2020
CH_4	**15**	**17**	**17**	**17**	**17**	**17**	**17**
Maize	2	4	5	5	5	5	5
Rice	3	3	2	3	2	3	2
Wheat	6	6	5	5	5	5	5
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Cotton	1	2	1	1	1	1	1
Grass Hay	+	+	+	+	+	+	+
Legume Hay	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Soybeans	1	2	2	2	2	2	2
Potatoes	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Maize	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+
Wheat	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+
Oats	+	+	+	+	+	+	+
Other Small Grains	+	+	+	+	+	+	+
Sorghum	+	+	+	+	+	+	+
Cotton	+	+	+	+	+	+	+
Grass Hay	+	+	+	+	+	+	+

Legume Hay	+	+	+	+	+	+	+
Peas	+	+	+	+	+	+	+
Sunflower	+	+	+	+	+	+	+
Tobacco	+	+	+	+	+	+	+
Vegetables	+	+	+	+	+	+	+
Chickpeas	+	+	+	+	+	+	+
Dry Beans	+	+	+	+	+	+	+
Lentils	+	+	+	+	+	+	+
Peanuts	+	+	+	+	+	+	+
Soybeans	+	+	+	+	+	+	+
Potatoes	+	+	+	+	+	+	+
Sugarbeets	+	+	+	+	+	+	+
CO	**315**	**363**	**340**	**339**	**338**	**337**	**336**
NO_x	**13**	**15**	**14**	**14**	**14**	**14**	**14**

+ Does not exceed 0.5 kt.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

A country-specific Tier 2 method is used to estimate greenhouse gas emissions from field burning of agricultural residues from 1990 to 2014 (for more details comparing the country-specific approach to the IPCC (2006) default approach, see Box 5-6), and a data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2020. The following equation is used to estimate the amounts of C and N released $(R_i, where\ i\ is\ C\ or\ N)$ from burning.

Equation 5-1: Elemental C or N Released through Oxidation of Crop Residues

$$R_i = CP \times RCR \times DMF \times F_i \times FB \ \times CE$$

$$FB \ = \frac{AB}{CAH}$$

where,

Crop Production (CP) = Annual production of crop, by state, kt crop production
Residue: Crop Ratio (RCR) = Amount of residue produced per unit of crop production, kt residue/kt crop production
Dry Matter Fraction (DMF) = Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
Fraction C or N (F_i) = Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
Fraction Burned (FB) = Proportion of residue biomass consumed, unitless
Combustion Efficiency (CE) = Proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively, unitless
Area Burned (AB) = Total area of crop burned, by state, ha
Crop Area Harvested (CAH) = Total area of crop harvested, by state, ha

Crop production data are available by state and year from USDA (2019) for twenty-one crops that are burned in the conterminous United States, including maize, rice, wheat, barley, oats, other small grains, sorghum, cotton, grass hay, legume hay, peas, sunflower, tobacco, vegetables, chickpeas, dry beans, lentils, peanuts, soybeans, potatoes, and sugarbeets.[25] Crop area data are based on the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018). In order to estimate total crop production, the crop yield data from USDA Quick Stats crop yields is multiplied by the NRI crop areas. The production data for the crop types are presented in Table 5-30. Alaska and Hawaii are not included in the current analysis, but there is a planned improvement to estimate residue burning emissions for these two states in a future Inventory.

The amount of elemental C or N released through oxidation of the crop residues is used in the following equation to estimate the amount of CH_4, CO, N_2O, and NO_x emissions (E_g, where g is the specific gas, i.e., CH_4, CO, N_2O, and NO_x) from the Field Burning of Agricultural Residues:

Equation 5-2: Emissions from Crop Residue Burning

$$E_g = R_i \times EF_g \times CF$$

where,

Emission ratio (EF_g) = emission ratio by gas, g CH_4-C or CO-C/g C released, or g N_2O-N or NO_x-N/g N released

Conversion Factor (CF) = conversion by molecular weight ratio of CH_4-C to C (16/12), CO-C to C (28/12), N_2O-N to N (44/28), or NO_x-N to N (30/14)

Box 5-6: Comparison of Tier 2 U.S. Inventory Approach and IPCC (2006) Default Approach

Emissions from Field Burning of Agricultural Residues are calculated using a Tier 2 methodology that is based on the method developed by the IPCC/UNEP/OECD/IEA (1997). The rationale for using the IPCC/UNEP/OECD/IEA (1997) approach rather than the method provided in the *2006 IPCC Guidelines* is as follows: (1) the equations from both guidelines rely on the same underlying variables (though the formats differ); (2) the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues; (3) the IPCC (2006) method provides emission factors based on the dry matter content rather emission rates related to the amount of C and N in the residues; and (4) the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from twenty-one crops.

A comparison of the methods in the current Inventory and the default IPCC (2006) approach was undertaken for 2014 to determine the difference in estimates between the two approaches. To estimate greenhouse gas emissions from field burning of agricultural residues using the IPCC (2006) methodology, the following equation—cf. IPCC (2006) Equation 2.27—was used with default factors and country-specific values for mass of fuel.

Equation 5-3: Estimation of Greenhouse Gas Emissions from Fire

$$Emissions\ (kt) = AB \times (M_B \times C_f) \times G_{ef} \times 10^{-6}$$

where,

Area Burned (AB) = Total area of crop burned (ha)

Mass of Fuel ($M_B \times C_f$) = IPCC (2006) default carbon fractions with fuel biomass consumption U.S.-Specific Values using NASS Statistics[26] (metric tons dry matter burnt ha^{-1})

Emission Factor (G_{ef}) = IPCC (2006) emission factor (g kg^{-1} dry matter burnt)

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[25] Sugarcane and Kentucky bluegrass (produced on farms for turf grass installations) may have small areas of burning that are not captured in the sample of locations that were used in the remote sensing analysis (see Planned Improvements).

[26] NASS yields are used to derive mass of fuel values because IPCC (2006) only provides default values for 4 of the 21 crops included in the Inventory.

The IPCC (2006) Tier 1 method approach resulted in 33 percent lower emissions of CH_4 and 53 percent lower emissions of N_2O compared to this Inventory. In summary, the IPCC/UNEP/OECD/IEA (1997) method is considered more appropriate for U.S. conditions because it is more flexible for incorporating country-specific data. Emissions are estimated based on specific C and N content of the fuel, which is converted into CH_4, CO, N_2O and NO_x, compared to IPCC (2006) approach that is based on dry matter rather than elemental composition.

Table 5-30: Agricultural Crop Production (kt of Product)

Crop	1990		2005		2013	2014
Maize	296,065		371,256		436,565	453,524
Rice	9,543		11,751		10,894	12,380
Wheat	79,805		68,077		67,388	62,602
Barley	9,281		5,161		4,931	5,020
Oats	5,969		2,646		1,806	2,042
Other Small Grains	2,651		2,051		1,902	2,492
Sorghum	23,687		14,382		18,680	18,436
Cotton	4,605		6,106		3,982	4,396
Grass Hay	44,150		49,880		45,588	46,852
Legume Hay	90,360		91,819		79,669	82,844
Peas	51		660		599	447
Sunflower	1,015		1,448		987	907
Tobacco	1,154		337		481	542
Vegetables	0		1,187		1,844	2,107
Chickpeas	0		5		0	0
Dry Beans	467		1,143		1,110	1,087
Lentils	0		101		72	76
Peanuts	1,856		2,176		2,072	2,735
Soybeans	56,612		86,980		94,756	110,560
Potatoes	18,924		20,026		20,234	19,175
Sugarbeets	24,951		25,635		31,890	31,737

Note: The amount of crop production has not been compiled for 2015 to 2020 so a data splicing method is used to estimate emissions for this portion of the time series.

The area burned is determined based on an analysis of remote sensing products (McCarty et al. 2009, 2010, 2011). The presence of fires has been analyzed at 3,600 survey locations in the NRI from 1990 to 2002 with LANDFIRE data products developed from 30 m Landsat imagery (LANDFIRE 2014), and from 2003 through 2014 using 1 km Moderate Resolution Imaging Spectroradiometer imagery (MODIS) Global Fire Location Product (MCD14ML) using combined observations from Terra and Aqua satellites (Giglio et al. 2006). A sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states.

For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events. Several variables are tested in the logistical regression including a) the historical level of burning in each state (high, medium or low levels of burning) based on an analysis by McCarty et al. (2011), b) year that state laws limit burning of fields, in addition to c) mean annual precipitation and mean annual temperature from a 4-kilometer gridded product from the PRISM Climate Group (2015). A K-fold model fitting procedure is used due to low frequency of burning and likelihood that outliers could influence the model fit. Specifically, the model is trained with a random selection of sample locations and evaluated with the remaining sample. This process is repeated ten times to select a model that is most common among the set of ten, and avoid models that appear to be influenced by outliers due to the random draw of survey locations for training the model. In order to address uncertainty, a Monte Carlo analysis is used to sample the parameter estimates for the logistical regression model and produce one thousand estimates of burning for each crop in the remaining forty-two states included in this Inventory. State-level area burned data are divided by state-level crop area data to estimate the percent of crop area burned by crop type for each state. Table 5-31 shows the resulting percentage of crop residue burned at the national scale by crop type. State-level estimates are also available upon request.

Table 5-31: U.S. Average Percent Crop Area Burned by Crop (Percent)

Crop	1990	2005	2013	2014
Maize	+%	+%	+%	+%
Rice	8%	8%	4%	6%
Wheat	1%	2%	2%	1%
Barley	1%	+%	1%	1%
Oats	1%	1%	2%	1%
Other Small Grains	1%	1%	1%	1%
Sorghum	1%	1%	1%	1%
Cotton	1%	1%	1%	1%
Grass Hay	+%	+%	+%	+%
Legume Hay	+%	+%	+%	+%
Peas	+%	+%	+%	+%
Sunflower	+%	+%	+%	+%
Tobacco	2%	2%	3%	3%
Vegetables	0%	+%	+%	+%
Chickpeas	0%	1%	0%	0%
Dry Beans	1%	1%	+%	+%
Lentils	0%	+%	+%	+%
Peanuts	3%	3%	3%	3%
Soybeans	+%	+%	1%	1%
Potatoes	+%	+%	+%	+%
Sugarbeets	+%	+%	+%	+%

+ Does not exceed 0.5 percent

Additional parameters are needed to estimate the amount of burning, including residue: crop ratios, dry matter fractions, carbon fractions, nitrogen fractions and combustion efficiency. Residue: crop product mass ratios, residue dry matter fractions, and the residue N contents are obtained from several sources (IPCC 2006 and sources at bottom of Table 5-32). The residue C contents for all crops are based on IPCC (2006) default value for herbaceous biomass. The combustion efficiency is assumed to be 90 percent for all crop types (IPCC/UNEP/OECD/IEA 1997). See Table 5-32 for a summary of the crop-specific conversion factors. Emission ratios and mole ratio conversion factors for all gases are based on the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) (see Table 5-33).

Table 5-32: Parameters for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Combustion Efficiency (Fraction)
Maize	0.707	0.56	0.47	0.01	0.90
Rice	1.340	0.89	0.47	0.01	0.90
Wheat	1.725	0.89	0.47	0.01	0.90
Barley	1.181	0.89	0.47	0.01	0.90
Oats	1.374	0.89	0.47	0.01	0.90
Other Small Grains	1.777	0.88	0.47	0.01	0.90
Sorghum	0.780	0.60	0.47	0.01	0.90
Cotton	7.443	0.93	0.47	0.01	0.90
Grass Hay	0.208	0.90	0.47	0.02	0.90
Legume Hay	0.290	0.67	0.47	0.01	0.90
Peas	1.677	0.91	0.47	0.01	0.90
Sunflower	1.765	0.88	0.47	0.01	0.90
Tobacco	0.300	0.87	0.47	0.01	0.90
Vegetables	0.708	0.08	0.47	0.01	0.90
Chickpeas	1.588	0.91	0.47	0.01	0.90
Dry Beans	0.771	0.90	0.47	0.01	0.90
Lentils	1.837	0.91	0.47	0.02	0.90
Peanuts	1.600	0.94	0.47	0.02	0.90
Soybeans	1.500	0.91	0.47	0.01	0.90
Potatoes	0.379	0.25	0.47	0.02	0.90
Sugarbeets	0.196	0.22	0.47	0.02	0.90

Notes: Chickpeas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Cotton: Combined sources (Heitholt et al. 1992; Halevy 1976; Wells and Meredith 1984; Sadras and Wilson 1997; Pettigrew and Meredith 1997; Torbert and Reeves 1994; Gerik et al. 1996; Brouder and Cassmen 1990; Fritschi et al. 2003; Pettigrew et al. 2005; Bouquet and Breitenbeck 2000; Mahroni and Aharonov 1964; Bange and Milroy 2004; Hollifield et al. 2000; Mondino et al. 2004; Wallach et al. 1978).

Lentils: IPCC (2006), Table 11.2; Beans & pulses.

Peas: IPCC (2006), Table 11.2; values are for Beans & pulses.

Peanuts: IPCC (2006); Table 11.2; Root ratio and belowground N content values are for Root crops, other.

Sugarbeets: IPCC (2006); Table 11.2; values are for Tubers.

Sunflower: IPCC (2006), Table 11.2; values are for Grains.

Sugarcane: combined sources (Wiedenfels 2000, Dua and Sharma 1976; Singels & Bezuidenhout 2002; Stirling et al. 1999; Sitompul et al. 2000).

Tobacco: combined sources (Beyaert 1996; Moustakas and Ntzanis 2005; Crafts-Brandner et al. 1994; Hopkinson 1967; Crafts-Brandner et al. 1987).

Vegetables (Combination of carrots, lettuce/cabbage, melons, onions, peppers and tomatoes):

Carrots: McPharlin et al. (1992); Gibberd et al. (2003); Reid and English (2000); Peach et al. (2000); see IPCC Tubers for R:S and N fraction.

Lettuce, cabbage: combined sources (Huett and Dettman 1991; De Pinheiro Henriques & Marcelis 2000; Huett and Dettman 1989; Peach et al. 2000; Kage et al. 2003; Tan et al. 1999; Kumar et al. 1994; MacLeod et al. 1971; Jacobs et al. 2004; Jacobs et al. 2001; Jacobs et al. 2002); values from IPCC Grains used for N fraction.

Melons: Valantin et al. (1999); squash for R:S; IPCC Grains for N fraction.

Onion: Peach et al. (2000), Halvorson et al. (2002); IPCC (2006) Tubers for N fraction.

Peppers: combined sources (Costa and Gianquinto 2002; Marcussi et al. 2004; Tadesse et al. 1999; Diaz-Perez et al. 2008); IPCC Grains for N fraction.

Tomatoes: Scholberg et al. (2000a,b); Akintoye et al. (2005); values for AGR-N and BGR-N are from Grains.

Table 5-33: Greenhouse Gas Emission Ratios and Conversion Factors

Gas	Emission Ratio	Conversion Factor
CH_4:C	0.005[a]	16/12
CO:C	0.060[a]	28/12
N_2O:N	0.007[b]	44/28
NO_x:N	0.121[b]	30/14

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).

[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

For this Inventory, new activity data on the burned areas have not been analyzed for 2015 to 2020. To complete the emissions time series, a linear extrapolation of the trend is applied to estimate the emissions in the last five years of the inventory. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH_4, N_2O, CO and NO_x for the last six years in the time series from 2015 to 2020 (Brockwell and Davis 2016). The Tier 2 method described previously will be applied to recalculate the emissions for the last six years in the time series (2015 to 2020) in a future Inventory.

In order to ensure time-series consistency, the same method is applied from 1990 to 2014, and a linear extrapolation method is used to approximate emissions for the remainder of the time series based on the emissions data from 1990 to 2014. This extrapolation method is consistent with data splicing methods in IPCC (2006).

Uncertainty

Emissions are estimated using a linear regression model with autoregressive moving-average (ARMA) errors for 2020. The linear regression ARMA model produced estimates of the upper and lower bounds to quantify uncertainty (Table 5-34), and the results are summarized in Table 5-34. Methane emissions from field burning of agricultural residues in 2020 are between 0.35 and 0.50 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 18 percent below and 18 percent above the 2020 emission estimate of 0.4 MMT CO_2 Eq. Nitrous oxide emissions are between 0.16 and 0.22 MMT CO_2 Eq., or approximately 17 percent below and 17 percent above the 2020 emission estimate of 0.2 MMT CO_2 Eq.

Table 5-34: Approach 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.4	0.35	0.50	-18%	18%
Field Burning of Agricultural Residues	N_2O	0.2	0.16	0.22	-17%	17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Due to data limitations, there are additional uncertainties in agricultural residue burning, particularly the potential omission of burning associated with Kentucky bluegrass (produced on farms for turf grass installation) and sugarcane (see Annex 5 on sugarcane).

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues is implemented with Tier 1 analyses, consistent with the U.S. Inventory QA/QC plan outlined in Annex 8. The previous Inventory included a term for burning efficiency that is not found in the IPCC/UNEP/OECD/IEA (1997) method. This term has been removed based on a QA/QC initiated by the UN Expert Review Team. In addition, the combustion efficiency term has been set to 90 percent to be consistent with the Tier 1 method in IPCC/UNEP/OECD/IEA (1997).

Recalculations Discussion

No recalculations have been conducted for this source category.

Planned Improvements

A key planned improvement is to estimate the emissions associated with field burning of agricultural residues in the states of Alaska and Hawaii. In addition, a new method is in development that will directly link agricultural residue burning with the Tier 3 methods that are used in several other source categories, including Agricultural Soil Management, *Cropland Remaining Cropland*, and Land Converted to Cropland chapters of the Inventory. The method is based on simulating burning events directly within the DayCent process-based model framework using information derived from remote sensing fire products as described in the Methodology section. This improvement will lead to greater consistency in the methods for across sources, ensuring mass balance of C and N in the Inventory analysis.

As previously noted in this chapter, remote sensing data were used in combination with a resource survey to estimate non-CO_2 emissions and these data did not allow identification of burning of sugarcane (see Annex 5). EPA has received feedback on this category/crop type, which includes average estimates of emissions of sugarcane burning found in academic literature. EPA is assessing this information identified in feedback, other available activity data, and an updated methodology, as part of Inventory improvements which EPA plans to implement for the 2023 submission.

6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land-use types including: Forest Land, Cropland, Grassland, Wetlands, and Settlements (as well as Other Land).

The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from *Land Converted to Forest Land* are included for aboveground biomass, belowground biomass, dead wood, litter, and C stock changes from mineral soils, while C stock changes from drained organic soils and all non-CO_2 emissions from *Land Converted to Forest Land* are included in the fluxes from *Forest Land Remaining Forest Land* as it is not currently possible to separate these fluxes by conversion category.

Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, and *Land Converted to Grassland*. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic C stocks in mineral and organic soils due to land use and management, and for the subcategories of Forest Land Converted to Cropland and Forest Land Converted to Grassland, the changes in aboveground biomass, belowground biomass, dead wood, and litter C stocks are also reported. The greenhouse gas flux from Grassland Remaining Grassland also includes estimates of non-CO_2 emissions from grassland fires occurring on both Grassland Remaining Grassland and *Land Converted to Grassland*.

Fluxes from *Wetlands Remaining Wetlands* include changes in C stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil C stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. In addition, CH_4 emissions from reservoirs and other constructed waterbodies are included for the subcategory Flooded Land Remaining Flooded Land. Estimates for Land Converted to Wetlands include aboveground and belowground biomass, dead organic matter and soil C stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands. Carbon dioxide (CO_2) and CH_4 emissions are included for reservoirs and other constructed waterbodies under the subcategory Land Converted to Flooded Land.

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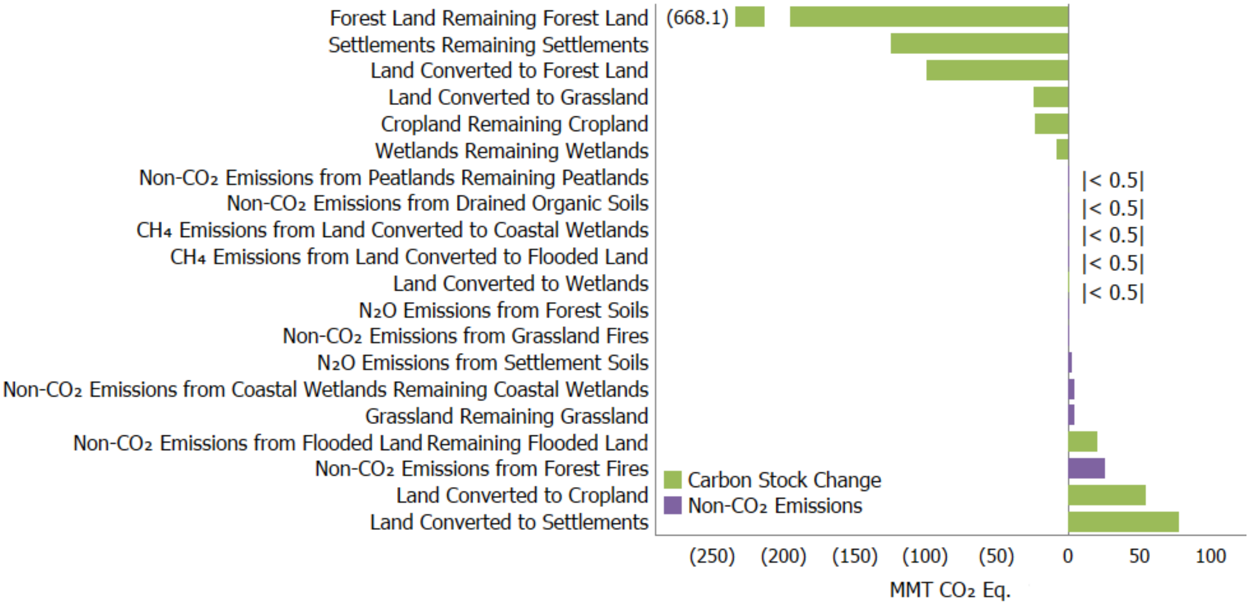
[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Fluxes from *Settlements Remaining Settlements* include changes in C stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from *Land Converted to Settlements* includes changes in C stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the C stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory *Forest Land Converted to Settlements*.

In 2020 the land use, land-use change, and forestry (LULUCF) sector resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.2 MMT CO_2 Eq.[2] This represents an offset of approximately 13.6 percent of total (i.e., gross) greenhouse gas emissions in 2020. Emissions of CH_4 and N_2O from LULUCF activities in 2020 were 38.1 and 15.2 MMT CO_2 Eq., respectively, and combined represent 0.9 percent of total greenhouse gas emissions.[3] In 2020 the overall net flux from LULUCF resulted in a removal of 758.9 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land-use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2020 time series are shown in Figure 6-2.

Figure 6-1: 2020 LULUCF Chapter Greenhouse Gas Sources and Sinks



Note: Parentheses in horizontal axis indicate net sequestration.

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[2] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland*, Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 6-2: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

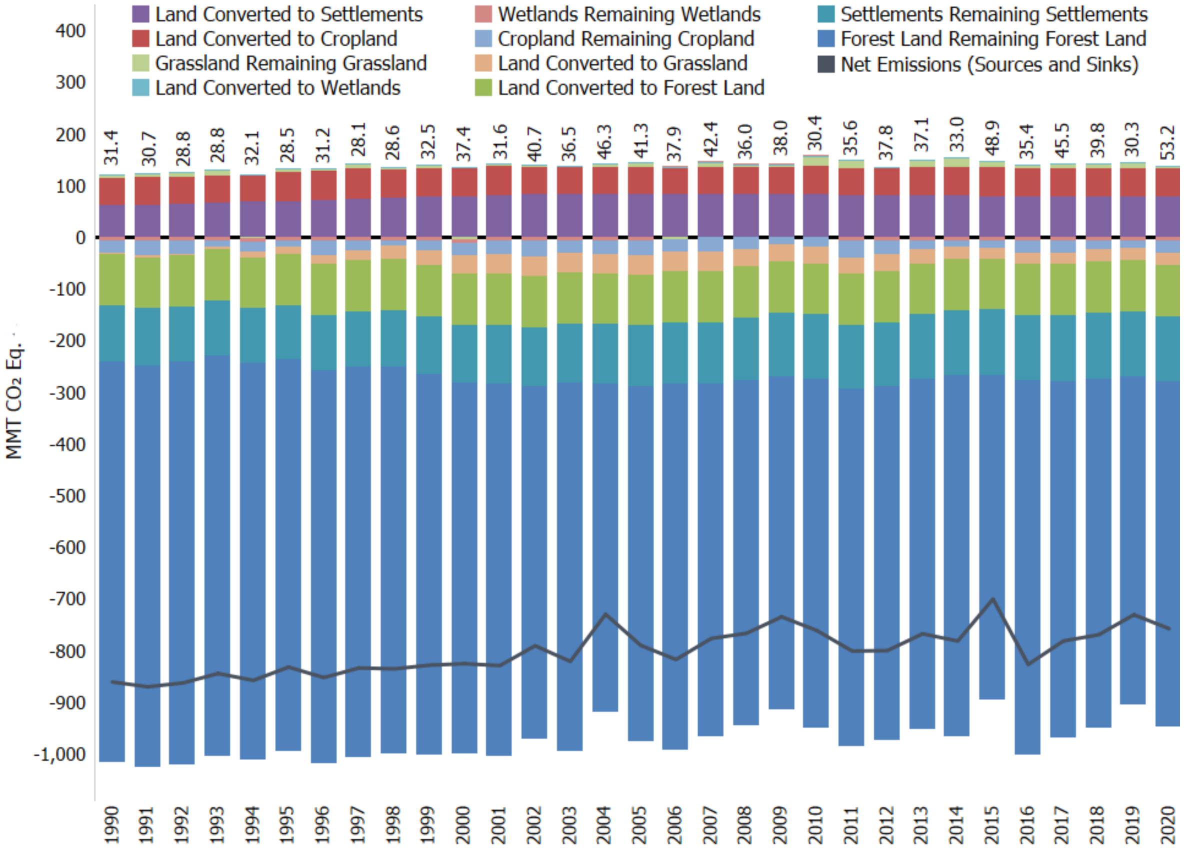

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Forest Land Remaining Forest Land	**(769.7)**	**(674.0)**	**(717.3)**	**(670.1)**	**(664.6)**	**(631.8)**	**(642.2)**
Changes in Forest Carbon Stocks[a]	(774.0)	(687.3)	(725.6)	(688.3)	(677.1)	(634.8)	(668.1)
Non-CO_2 Emissions from Forest Fires[b]	4.1	12.8	7.8	17.7	11.9	2.5	25.3
N_2O Emissions from Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.6)**	**(99.1)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**
Changes in Forest Carbon Stocks[e]	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	**(23.2)**	**(29.0)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**	**(23.3)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland	**51.8**	**52.0**	**54.1**	**54.3**	**54.0**	**53.9**	**54.4**
Changes in all Ecosystem Carbon Stocks[f]	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland	**7.1**	**9.4**	**8.6**	**9.9**	**10.3**	**13.1**	**5.1**
Changes in Mineral and Organic Soil Carbon Stocks	6.9	8.7	8.0	9.3	9.7	12.4	4.5
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.7	0.6	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(3.1)**	**(37.0)**	**(22.6)**	**(22.7)**	**(22.4)**	**(21.5)**	**(24.1)**
Changes in all Ecosystem Carbon Stocks[f]	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)
Wetlands Remaining Wetlands	**14.7**	**17.2**	**15.8**	**15.9**	**15.9**	**15.9**	**15.8**

Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.8	0.8	0.8	0.7
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.2	0.2	0.2
CH_4 Emissions from Flooded Land Remaining Flooded Land	18.2	19.8	19.9	19.9	19.9	19.9	19.9
Land Converted to Wetlands	**7.2**	**1.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.9	0.3	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.6	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(121.5)**	**(125.3)**	**(124.9)**	**(124.5)**	**(123.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	16.0	16.0	15.9	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(129.8)	(129.8)	(129.8)	(129.8)	(129.8)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.3	2.4	2.4	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(10.0)	(13.8)	(13.4)	(13.1)	(12.2)
Land Converted to Settlements	**60.8**	**82.8**	**77.8**	**77.9**	**78.0**	**77.9**	**77.9**
Changes in all Ecosystem Carbon Stocks[f]	60.8	82.8	77.8	77.9	78.0	77.9	77.9
LULUCF Emissions[i]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change[j]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[k]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.* Carbon stock changes from drained organic soils are included with th*e Forest Land Remaining Forest Land* forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to*

Coastal Wetlands, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[j] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The C stock changes and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total net C sequestration in the LULUCF sector decreased by approximately 9.0 percent between 1990 and 2020. This decrease was primarily due to a decline in the rate of net C accumulation in Forest Land*,* as well as an increase in emissions from Land Converted to Settlements.[4] Specifically, there was a net C accumulation in *Settlements Remaining Settlements*, which increased from 1990 to 2020, while the net C accumulation in *Forest Land Remaining Forest Land* and Land Converted to Wetlands slowed over this period. Net C accumulation remained steady from 1990 to 2020 in *Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, and *Wetlands Remaining Wetlands*, while net C accumulation fluctuated in Grassland Remaining Grassland.

Flooded Land Remaining Flooded Land*,* included for the first time in this year's estimates, was the largest source of CH_4 emissions from LULUCF in 2020, totaling 19.9 MMT CO_2 Eq. (797kt of CH_4). Forest fires resulted in CH_4 emissions of 13.6MMT CO_2 Eq. (545kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8MMT CO_2 Eq. (154 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). Land Converted to Flooded Land and Land Converted to Wetlands each resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (7 kt of CH_4). *Drained Organic Soils* on forest lands and Peatlands Remaining Peatlands resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

For N_2O emissions, forest fires were the largest source from LULUCF in 2020, totaling 11.7 MMT CO_2 Eq. (39 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2020 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 23.2 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2020 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions. Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* resulted in N_2O emissions of 0.2 MMT CO_2 Eq. (1 kt of N_2O). Drained Organic Soils on forest lands resulted in N_2O emissions of 0.1 MMT CO_2 Eq. (less than 0.5 kt of N_2O), and Peatlands Remaining Peatlands resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Carbon Stock Change (CO_2)[a]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
Forest Land Remaining Forest Land	(774.0)	(687.3)	(725.6)	(688.3)	(677.1)	(634.8)	(668.1)
Land Converted to Forest Land	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland	6.9	8.7	8.0	9.3	9.7	12.4	4.5
Land Converted to Grassland	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)
Wetlands Remaining Wetlands	(7.4)	(6.5)	(8.0)	(8.0)	(8.0)	(8.0)	(8.1)
Land Converted to Wetlands	4.3	0.8	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(109.6)	(116.6)	(123.8)	(127.7)	(127.3)	(127.0)	(126.1)
Land Converted to Settlements	60.8	82.8	77.8	77.9	78.0	77.9	77.9
CH_4	**27.2**	**30.9**	**28.3**	**34.0**	**30.7**	**25.5**	**38.1**
Forest Land Remaining Forest Land:	2.3	6.5	3.9	9.5	6.2	1.1	13.6

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[4] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

Forest Fires[b]							
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[c]	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	18.2	19.8	19.9	19.9	19.9	19.9	19.9
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.6	0.2	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**4.2**	**10.5**	**7.1**	**11.5**	**9.1**	**4.8**	**15.2**
Forest Land Remaining Forest Land: Forest Fires[b]	1.8	6.3	3.9	8.2	5.7	1.3	11.7
Forest Land Remaining Forest Land: Forest Soils[f]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Forest Land Remaining Forest Land: Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[c]	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[e]	2.0	3.1	2.2	2.3	2.4	2.4	2.5
LULUCF Carbon Stock Change[a]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Emissions[g]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
LULUCF Sector Net Total[h]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[d] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland*.

[e] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[f] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from Flooded Land Remaining Flooded Land, Land Converted to Flooded Land, and *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[h] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Carbon Stock Change (CO_2)[a]	**(892,027)**	**(831,126)**	**(862,045)**	**(826,667)**	**(809,026)**	**(760,820)**	**(812,176)**
Forest Land Remaining Forest Land	(773,993)	(687,271)	(725,571)	(688,301)	(677,101)	(634,824)	(668,057)
Land Converted to Forest Land	(98,585)	(99,068)	(99,454)	(99,523)	(99,518)	(99,520)	(99,521)
Cropland Remaining Cropland	(23,176)	(29,002)	(22,731)	(22,293)	(16,597)	(14,544)	(23,335)
Land Converted to Cropland	51,784	52,032	54,107	54,273	53,975	53,935	54,380
Grassland Remaining Grassland	6,940	8,734	7,958	9,308	9,670	12,425	4,497
Land Converted to Grassland	(3,141)	(36,951)	(22,553)	(22,693)	(22,397)	(21,485)	(24,101)
Wetlands Remaining Wetlands	(7,399)	(6,549)	(8,046)	(7,954)	(7,994)	(8,034)	(8,084)
Land Converted to Wetlands	4,329	807	254	258	265	271	279
Settlements Remaining Settlements	(109,567)	(116,642)	(123,794)	(127,679)	(127,299)	(126,977)	(126,128)
Land Converted to Settlements	60,793	82,784	77,784	77,938	77,970	77,932	77,895
CH_4	**1,088**	**1,235**	**1,131**	**1,359**	**1,226**	**1,022**	**1,522**
Forest Land Remaining Forest Land: Forest Fires[b]	92	260	154	381	249	45	545
Forest Land Remaining Forest Land: Drained Organic Soils[d]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[c]	3	13	11	12	12	12	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	729	792	797	797	797	797	797
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	153	153	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	103	9	7	7	7	7	7
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	8	8	7	7	7
N_2O	**14**	**35**	**24**	**39**	**31**	**16**	**51**
Forest Land Remaining Forest Land: Forest Fires[b]	6	21	13	27	19	4	39
Forest Land Remaining Forest Land: Forest Soils[f]	+	2	2	2	2	2	2
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[c]	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	+	+	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[e]	7	10	8	8	8	8	8

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[d] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland*.
[e] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.
[f] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Each year, some emission and sink estimates in the LULUCF sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emissions and sinks estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate. Of the updates implemented for this Inventory, the most significant include (1) Flooded Land Remaining Flooded Land and Land Converted to Flooded Land: new categories included for the first time based on new guidance in the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*, (2) Forest Lands: use of new data from the National Forest Inventory (NFI), compiling population estimates of carbon stocks and stock changes using NFI data from each U.S. state and summing over all states to obtain the national estimates, refined estimates in the Digital General Soil Map, and new data on area burned from the Monitoring Trends in Burn Severity (MTBS) data product; and (3) Coastal Wetlands: an updated NOAA report on fisheries data was released in 2021 and was used in estimating N_2O emissions from aquaculture. Together, these updates for 2019 decreased total sequestration of CO_2 by 51.6 MMT CO_2 Eq. (5.7 percent) and decreased total non-CO_2 emissions by 16.2 MMT CO_2 Eq. (81.5 percent), compared to the previous Inventory (i.e., 1990 to 2019). For more information on specific methodological updates, please see the Recalculations discussion within the respective source category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states, however, for Hawaii and Alaska some emissions and removals from land use and land use change are not included (see chapter sections on Uncertainty and Planned Improvements for more details). In addition, U.S. Territories are not included. EPA continues to review available data on an ongoing basis to include emissions and removals from U.S. Territories in future inventories to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this Inventory.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventories: Wetlands,* and the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[5] The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations, but rather, this Chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself,

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[5] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land-use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (See IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land-use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[6] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[7] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[8]

The total land area included in the United States Inventory is 936 million hectares across the 50 states.[9] Approximately 886 million hectares of this land base is considered managed and 50 million hectares is unmanaged, which has not changed much over the time series of the Inventory (Table 6-5). In 2020, the United States had a total of 282 million hectares of managed Forest Land (0.03 percent decrease compared to 1990). There are 162 million hectares of cropland (7.2 percent decrease compared to 1990), 337 million hectares of managed Grassland (0.01 percent increase compared to 1990), 39 million hectares of managed Wetlands (1.8 percent increase compared to 1990), 45 million hectares of Settlements (34 percent increase compared to 1990), and 22 million hectares of managed Other Land (2.4 percent increase compared to 1990) (Table 6-5).

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[6] NRI data are available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[7] FIA data are available at http://www.fia.fs.fed.us/tools-data/default.asp.

[8] NLCD data are available at http://www.mrlc.gov/ and MRLC is a consortium of several U.S. government agencies.

[9] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future Inventories. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are reported mostly as managed.[10] In addition, C stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (e.g., Grassland Remaining Grassland within interior Alaska).[11,12] There are also discrepancies in the inventory emissions data and the land representation section because new FIA data were used in the inventory analysis, but were not incorporated into the land representation analysis due to timing of data availability and resources to complete the analysis. The land representation analysis will incorporate the new time series of FIA data int the next Inventory. In addition, planned improvements are under development to estimate C stock changes and greenhouse gas emissions on all managed land and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns (Figure 6-3). Forest Land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2016	2017	2018	2019[a]	2020[a]
Managed Lands	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**
Forest	281,621	281,681	281,796	281,652	281,546	281,546	281,546
Croplands	174,471	165,727	161,933	161,933	161,933	161,933	161,933
Grasslands	336,840	337,621	336,657	336,781	336,863	336,863	336,863
Settlements	33,446	40,469	44,795	44,797	44,797	44,797	44,797
Wetlands	38,422	39,017	39,089	39,108	39,132	39,132	39,132
Other	21,715	21,997	22,243	22,243	22,243	22,243	22,243
Unmanaged Lands	**49,681**	**49,684**	**49,683**	**49,683**	**49,683**	**49,683**	**49,683**
Forest	9,243	8,829	8,208	8,208	8,208	8,208	8,208
Croplands	0	0	0	0	0	0	0
Grasslands	25,530	25,962	26,608	26,608	26,608	26,608	26,608
Settlements	0	0	0	0	0	0	0
Wetlands	4,166	4,166	4,165	4,165	4,165	4,165	4,165
Other	10,742	10,727	10,701	10,701	10,701	10,701	10,701
Total Land Areas	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**
Forest	290,864	290,510	290,004	289,860	289,754	289,754	289,754
Croplands	174,471	165,727	161,933	161,933	161,933	161,933	161,933
Grasslands	362,370	363,583	363,266	363,389	363,471	363,471	363,471
Settlements	33,446	40,469	44,795	44,797	44,797	44,797	44,797
Wetlands	42,589	43,183	43,254	43,273	43,297	43,297	43,297
Other	32,457	32,725	32,944	32,944	32,944	32,944	32,944

[a] Land use data were not updated in this Inventory and the data for 2019 and 2020 were assumed to be the same as in 2018.

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[10] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all Wetlands in the conterminous United States and Hawaii are reported as managed. See the Planned Improvements section of the Inventory for future refinements to the Wetland area estimates.

[11] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in the next Inventory.

[12] These “managed area” discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

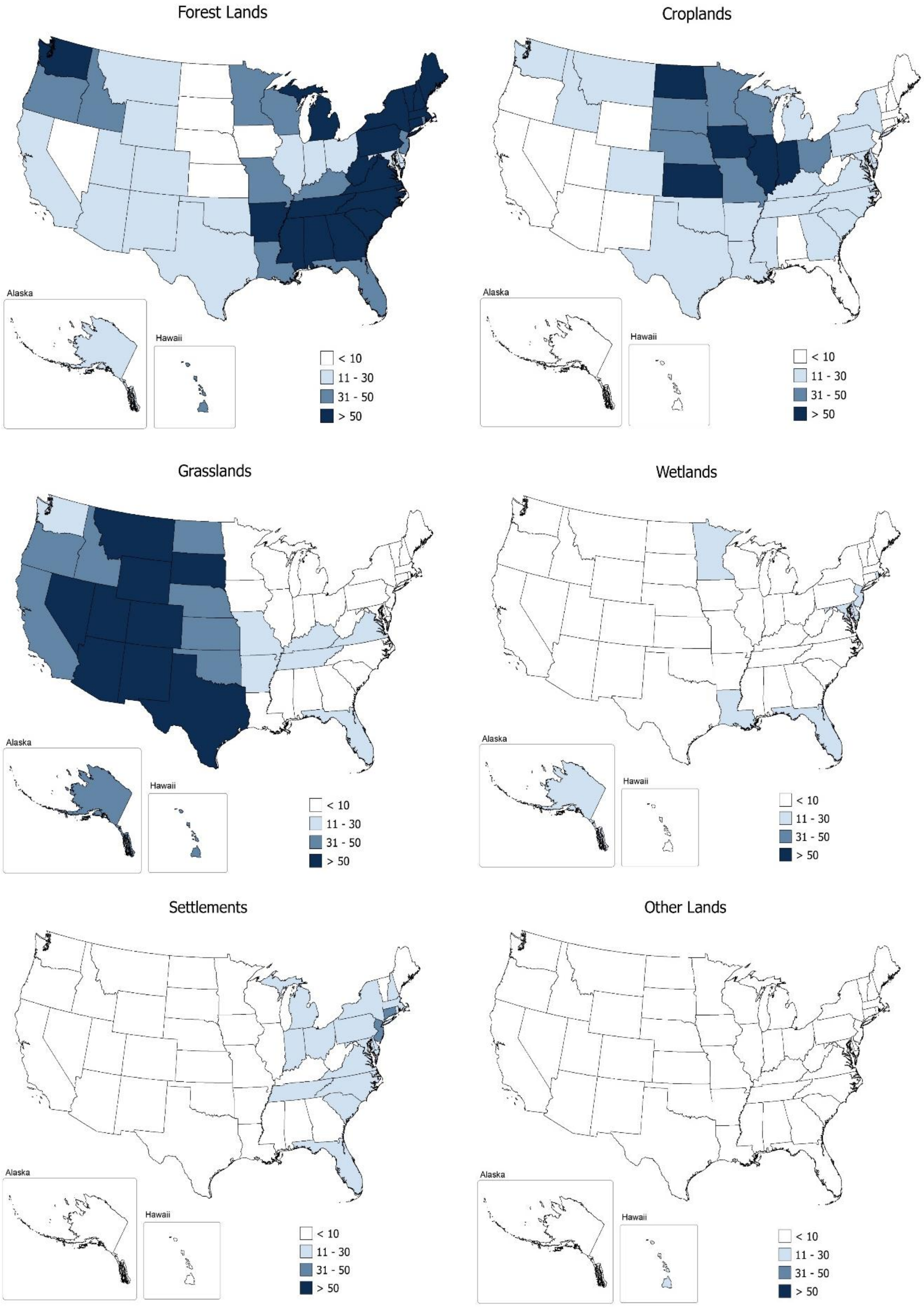
Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land Use & Land-Use Change Categories[a]	1990	2005	2016	2017	2018	2019	2020
Total Forest Land	**281,621**	**281,681**	**281,796**	**281,652**	**281,546**	**281,546**	**281,546**
FF	280,393	280,207	280,529	280,380	280,274	280,274	280,274
CF	169	167	134	135	135	135	135
GF	919	1,162	989	992	992	992	992
WF	77	28	25	25	25	25	25
SF	12	24	26	26	26	26	26
OF	50	93	93	93	93	93	93
Total Cropland	**174,471**	**165,727**	**161,933**	**161,933**	**161,933**	**161,933**	**161,933**
CC	162,163	150,304	148,885	148,884	148,884	148,884	148,884
FC	182	86	58	58	58	58	58
GC	11,738	14,820	12,609	12,609	12,609	12,609	12,609
WC	118	178	104	104	104	104	104
SC	75	100	99	99	99	99	99
OC	195	239	179	179	179	179	179
Total Grassland	**336,840**	**337,621**	**336,657**	**336,781**	**336,863**	**336,863**	**336,863**
GG	327,446	315,161	316,408	316,502	316,622	316,622	316,622
FG	593	560	553	583	545	545	545
CG	8,237	17,523	16,600	16,600	16,600	16,600	16,600
WG	176	542	308	308	308	308	308
SG	43	509	346	346	346	346	346
OG	345	3,328	2,442	2,442	2,442	2,442	2,442
Total Wetlands	**38,422**	**39,017**	**39,089**	**39,108**	**39,132**	**39,132**	**39,132**
WW	37,860	37,035	37,616	37,634	37,658	37,658	37,658
FW	83	59	54	54	54	54	54
CW	132	566	440	440	440	440	440
GW	297	1,187	836	836	836	836	836
SW	0	38	25	25	25	25	25
OW	50	133	118	118	118	118	118
Total Settlements	**33,446**	**40,469**	**44,795**	**44,797**	**44,797**	**44,797**	**44,797**
SS	30,585	31,522	38,210	38,210	38,210	38,210	38,210
FS	310	549	539	541	541	541	541
CS	1,237	3,602	2,452	2,452	2,452	2,452	2,452
GS	1,255	4,499	3,352	3,352	3,352	3,352	3,352
WS	4	61	46	46	46	46	46
OS	54	235	197	197	197	197	197
Total Other Land	**21,715**	**21,997**	**22,243**	**22,243**	**22,243**	**22,243**	**22,243**
OO	20,953	18,231	19,007	19,007	19,007	19,007	19,007
FO	41	70	90	90	90	90	90
CO	301	590	678	678	678	678	678
GO	391	2,965	2,331	2,331	2,331	2,331	2,331
WO	26	121	121	121	121	121	121
SO	2	20	16	16	16	16	16
Grand Total	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**

[a] The abbreviations are “F” for Forest Land, “C” for Cropland, “G” for Grassland, “W” for Wetlands, “S” for Settlements, and “O” for Other Lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., “FF” is Forest Land Remaining Forest Land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., “CF” is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for Wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include territories in future Inventories. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (see land use chapters e.g., Forest Land Remaining Forest Land for more information). Totals may not sum due to independent rounding.

Figure 6-3: Percent of Total Land Area for Each State in the General Land Use Categories for 2020



Methodology and Time-Series Consistency

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps derived from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society.[13]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

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[13] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions and peatlands due to insufficient activity data to estimate emissions and limited resources to improve the inventory. See the Planned Improvements section of the Inventory for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[14]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on C stocks. Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[15] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[16] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest Land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest Land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as Forest Land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for Forest Land. These areas are classified as Settlements. In addition, Forest Land does not include land that is predominantly under an agricultural land use (Oswalt et al. 2014).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[17] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for Forest Land. Lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[18]) are also classified as Cropland, as long as these areas do not meet the Forest Land criteria. Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.
- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both

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[14] There are some areas, such as Forest Land and Grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[15] See http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2015/Core-FIA-FG-7.pdf, page 22.

[16] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[17] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the Cropland land base.

[18] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as Grassland if there have been three or fewer years of continuous hay production.[19] Savannas, deserts, and tundra are considered Grassland.[20] Drained wetlands are considered Grassland if the dominant vegetation meets the plant cover criteria for Grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in Croplands (e.g., rice cultivation and cranberry production), Grasslands (e.g., wet meadows dominated by grass cover) and Forest Lands (e.g., Riparian Forests near waterways).
- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of Forest Land, and tracts of less than 10 acres (4.05 ha) that may meet the definitions for Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the Settlements category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), C stock changes and non-CO_2 emissions are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools. However, C stock changes and non-CO_2 emissions are estimated for *Land Converted to Other Land* during the first 20 years following conversion to account for legacy effects.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main sources for land-use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate C stock changes, N_2O, and CH_4 emissions on those

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[19] Areas with four or more years of continuous hay production are Cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

[20] *2006 IPCC Guidelines* do not include provisions to separate desert and tundra as land-use categories.

lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

		NRI	FIA	NLCD
Forest Land				
Conterminous United States				
	Non-Federal		•	
	Federal		•	
Hawaii				
	Non-Federal	•		
	Federal			•
Alaska				
	Non-Federal		•	•
	Federal		•	•
Croplands, Grasslands, Other Lands, Settlements, and Wetlands				
Conterminous United States				
	Non-Federal	•		
	Federal			•
Hawaii				
	Non-Federal	•		
	Federal			•
Alaska				
	Non-Federal			•
	Federal			•

National Resources Inventory

For the Inventory, the NRI is the official source of data for land use and land use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for Croplands and Grasslands (i.e., agricultural lands), and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (Note: most of the data has the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land-use data for non-federal lands in the conterminous United States and Hawaii. This Inventory incorporates data through 2015 from the NRI. The land use patterns are assumed to remain the same from 2016 through 2020 for this Inventory, but the time series will be updated when new data are integrated into the land representation analysis.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory and is another statistically-based survey for the conterminous United States in addition to the including southeast and south-central coastal Alaska. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest-land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for Forest Land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to 14 years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2015 through 2018; see Table A-202 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. In addition, FIA only records data for forest land across the land base in the conterminous United States and Alaska.[21] Consequently, gaps exist in the land representation when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of Forest Lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, and 2016 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015), and also for Alaska in 2001 and 2011 and Hawaii in 2001. A Land Cover Change Product is also available for Alaska from 2001 to 2011. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land use patterns are assumed to remain the same after the last year of data in the time series, which is 2001 for Hawaii, 2016 for the conterminous United States and 2011 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories derived from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

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[21] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land, Wetlands or Other Lands may be designated as unmanaged land;[23]
- All Forest Lands with active fire protection are considered managed;
- All Forest Lands designated for timber harvests are considered managed;
- All Grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged, remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest Lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data do lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance. Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged

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[23] All wetlands are considered managed in this Inventory with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land-use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for Forest Land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the Forest Land among the three databases. NRI and FIA have different criteria for classifying Forest Land in addition to different sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Any change in Forest Land Area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the Forest Land area and the amount of land designated as other land uses, such as the amount of Grassland, Cropland, and Wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. Adjustments are made in the *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, and Forest Land converted to other uses (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with Forest Land and conversions to and from Forest Land. There are three steps in this process. The first step involves adjustments to *Land Converted to Forest Land* (Grassland, Cropland, Settlements, Other Lands, and Wetlands), followed by a second step in which there are adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands), and finally the last step is to adjust *Forest Land Remaining Forest Land*.

In the first step, *Land Converted to Forest Land* in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal *Land Converted to Forest Land*, respectively. FIA data have not provided specific land-use categories that are converted to Forest Land in the past, but rather a sum of all *Land Converted to Forest Land*.[26] The NRI and NLCD provide information on specific land use conversions, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land use conversions into Forest Land for the state, prior to any adjustments. For example, if 50 percent of the land use change to Forest Land is associated with *Grassland Converted to Forest Land* in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of *Land Converted to Forest Land* is addressed by increasing or decreasing the area in *Grassland Converted to Forest Land*. Moreover, any increase or decrease in *Grassland Converted to Forest Land* in NRI or NLCD is addressed by a corresponding change in the area of Grassland Remaining Grassland*,* so that the total amount of managed area is not changed within an individual state.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for Forest Land converted to other uses. Similar to *Land Converted to Forest Land*, FIA have not provided information

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[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base derived from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

[26] The FIA program has started to collect data on the specific land uses that are converted to Forest Land, which will be further investigated and incorporated into a future Inventory.

on the specific land-use changes in the past,[27] and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets.

In the final step, the area of *Forest Land Remaining Forest Land* in a given state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in *Forest Land Remaining Forest Land* is associated with an under- or over-prediction of Grassland Remaining Grassland and *Wetlands Remaining Wetlands* in the NRI and NLCD. This step also assumes that there are no changes in the land use conversion categories. Therefore, corresponding increases or decreases are made in the area estimates of Grassland Remaining Grassland and *Wetlands Remaining Wetlands* from the NRI and NLCD. This adjustment balances the change in *Forest Land Remaining Forest Land* area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

The modified NRI data are then aggregated to provide the land-use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land in the conterminous United States and Alaska. FIA does have survey plots in Alaska that are used to determine the C stock changes, and the associated area data for this region are harmonized with the NLCD using the methods described above. NRI is used in the current report to provide Forest Land areas on non-federal lands in Hawaii, and NLCD is used for federal lands. FIA data is being collected in Hawaii and U.S. Territories, however there is insufficient data to make population estimates for this Inventory.
- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD is used to determine Cropland area and soil C stock changes on federal lands in the conterminous United States and Hawaii. NLCD is also used to determine croplands in Alaska, but C stock changes are not estimated for this region in the current Inventory.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and non-CO_2 greenhouse emissions on Grassland. Grassland area and soil C stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current Inventory does not include C stock changes in these areas.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]

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[27] The FIA program has started to collect data on specific land uses following conversion from Forest Land, which will be further investigated and incorporated into a future Inventory.

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acres (4.05 ha) threshold and are Grassland, they are classified as Grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories, is categorized as Other Land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may also meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as Cropland if they are used for crop production, such as rice, or as Grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the Inventory if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy, and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land use change. Regardless, the Census does provide sufficient information to provide a check on the Inventory data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares derived from the combined NRI, FIA, and NLCD data. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4

percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series, thus the land use areas for 2020 are assumed the same as 2019.

Planned Improvements

The next (i.e., 1990 through 2021) Inventory will be improved by using new NRI, FIA and possibly NLCD data to update the time series for land representation, providing consistency between the total area of managed land in the land representation section and the remainder of the Inventory. Another key planned improvement for the Inventory is to fully incorporate area data by land-use type for U.S. Territories. Fortunately, most of the managed land in the United States is included in the current land-use data, but a complete reporting of all lands in the United States is a key goal for the near future. Preliminary land-use area data for U.S. Territories by land-use category are provided in Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national Inventory as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the Inventory. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico so the NLCD was used for this area. The final selection of land-cover products for these territories is still under discussion. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land-Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the Inventory using the NOAA C-CAP land cover product.

The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for the next (i.e., 1990 through 2021) Inventory is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. In addition, the current Inventory does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRF Category 4A1)

Changes in Forest Carbon Stocks (CRF Category 4A1)

Delineation of Carbon Pools

For estimating carbon (C) stocks or stock change (flux), C in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes all duff, humus, and fine woody debris above the mineral soil and includes woody fragments with diameters of up to 7.5 cm.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

In addition, there are two harvested wood pools included when estimating C flux:

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined C storage pools and the atmosphere as a result of biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and is also transferred to the litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest C is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of all harvested biomass C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest C stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in C stocks in the five C storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining C stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states and Alaska and inventories have been initiated in Hawaii and some of the U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the C estimates (Domke et al. 2016; Domke et al. 2017). First, the total C stocks are estimated for each C storage pool at the individual NFI plot, next the annual net changes in C stocks for each pool are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in C stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (See Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the C stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years. The methods and data used to delineate forest C stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of modeling approaches for carbon estimation were used in this Inventory.

Forest Area in the United States

Approximately 32 percent of the U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section 6.1 Representation of the U.S. Land Base. All annual NFI plots included in the public FIA database as of August 2021 (which includes data collected through 2020 – note that the ongoing COVID 19 pandemic has resulted in delays in data collection in many states) were used in this Inventory. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. The NFIs from each of the conterminous 48 states (CONUS; USDA Forest Service 2022a, 2022b) and Alaska comprise an estimated 282 million hectares of forest land that are considered managed and are included in the current Inventory. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual NFI data through 2020 for all states (USDA Forest Service 2022b; Nelson et al. 2020). Sufficient annual NFI data are not yet available for Hawaii and the U.S. Territories to include them in this section of the Inventory but estimates of these areas are included in Oswalt et al. (2019). While Hawaii and U.S. Territories have relatively small areas of forest land and thus may not substantially influence the overall C budget for forest land, these regions will be added to the forest C estimates as sufficient data become available. Since HI was not included in this section of the current Inventory there are small differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base.[29] Agroforestry systems that meet the definition of forest land are also not currently included in the current Inventory since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI)[30] of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, and Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than the forest land removed from production because it does not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019). The southern region of the United States contains the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the CONUS and Alaska represented here is stable but there are substantial conversions as described in Section 6.1 Representation of the U.S. Land Base and each of the land conversion sections for each land use category (e.g., Land Converted to Cropland, *Land Converted to Grassland*). The major influences on the net C flux from forest land across the 1990 to 2020 time series are management activities, natural disturbance, particularly wildfire, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other C storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C in the aboveground biomass pool.[31] Though harvesting forests removes much of the C in aboveground biomass (and possibly changes C density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is about double the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in *Forest Land Remaining Forest Land* are captured in the estimates of C stocks and fluxes presented in this section.

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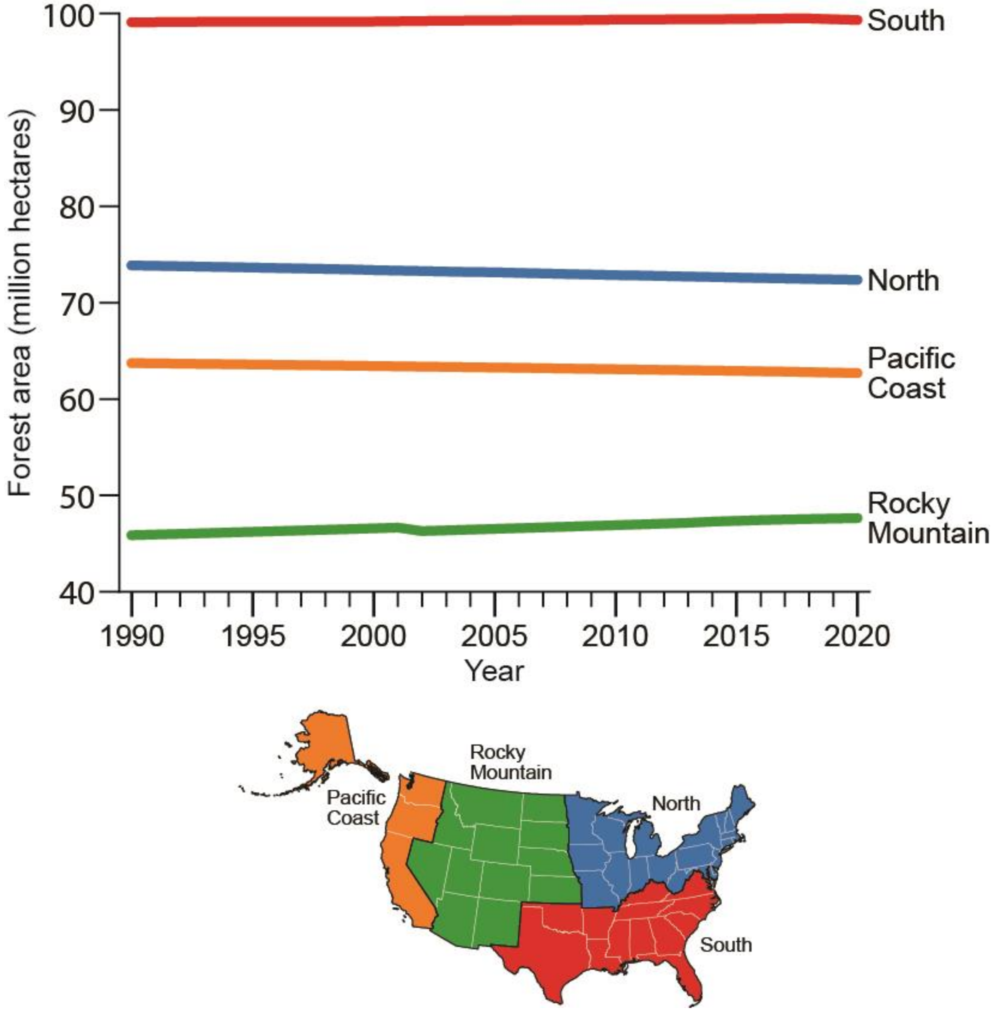
[29] See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

[30] The Natural Resources Inventory of the USDA Natural Resources Conservation Service is described in Section 6.1 Representation of the U.S. Land Base.

[31] The term “biomass density” refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. A carbon fraction of 0.5 is used to convert dry biomass to C (USDA Forest Service 2022d).

Figure 6-4: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and Alaska (1990-2020)



Forest Carbon Stocks and Stock Change

In *Forest Land Remaining Forest Land*, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net uptake (i.e., net sequestration or accumulation) of C each year from 1990 through 2020. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net C fluxes. Because most of the timber harvested from U.S. forest land is used in wood products, and many discarded wood products are disposed of in SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). Maintaining current harvesting practices and regeneration activities on these forested lands, along with continued input of harvested products into the HWP pool, C stocks in the *Forest Land Remaining Forest Land* category are likely to continue to increase in the near term, though possibly at a lower rate. Changes in

C stocks in the forest ecosystem and harvested wood pools associated with *Forest Land Remaining Forest Land* were estimated to result in net uptake of 668.1 MMT CO_2 Eq. (182.2 MMT C) in 2020 (Table 6-8, Table 6-9, Table A-210, Table A-211 and state-level estimates in Table A-214). The estimated net uptake of C in the Forest Ecosystem was 584.4 MMT CO_2 Eq. (159.4 MMT C) in 2020 (Table 6-8 and Table 6-9). The majority of this uptake in 2020, 398.7 MMT CO_2 Eq. (108.7 MMT C), was from aboveground biomass. Overall, estimates of average C density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 198 MT C ha^{-1} from 1990 to 2020. This was calculated by dividing the Forest Land area estimates by Forest Ecosystem C Stock estimates for every year (see Table 6-10 and Table A-212) and then calculating the mean across the entire time series, i.e., 1990 through 2020. The increasing forest ecosystem C density when combined with relatively stable forest area results in net C accumulation over time. Aboveground live biomass is responsible for the majority of net C uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in C density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series and much of this variability can be attributed to severe fire years. The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the CONUS. In Alaska, more than 11 percent of forest ecosystem C is stored in the litter carbon pool whereas in the CONUS only 7 percent of the total ecosystem C stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) which is why there are substantial C losses in this pool during severe fire years (Figure 6-5, Table A-227).

The estimated net uptake of C in HWP was 83.6 MMT CO_2 Eq. (22.8 MMT C) in 2020 (Table 6-8, Table 6-9, Table A-210, and Table A-211). The majority of this uptake, 63.6 MMT CO_2 Eq. (17.3 MMT C), was from wood and paper in SWDS. Products in use were an estimated 20.0 MMT CO_2 Eq. (5.5 MMT C) in 2020.

Table 6-8: Net CO_2 Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Forest Ecosystem	**(650.2)**	**(581.2)**	**(630.4)**	**(588.1)**	**(583.0)**	**(546.0)**	**(584.4)**
Aboveground Biomass	(462.5)	(416.3)	(432.7)	(407.7)	(406.6)	(393.1)	(398.7)
Belowground Biomass	(94.2)	(84.2)	(86.3)	(80.9)	(80.8)	(78.1)	(79.1)
Dead Wood	(96.8)	(96.8)	(106.4)	(99.8)	(102.0)	(97.0)	(101.5)
Litter	0.6	16.0	(3.1)	(1.9)	1.3	22.8	(1.9)
Soil (Mineral)	3.0	(0.3)	(5.6)	(1.1)	4.1	(0.6)	(4.1)
Soil (Organic)	(0.9)	(0.3)	3.0	2.5	0.3	(0.7)	0.2
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(95.1)**	**(100.2)**	**(94.1)**	**(88.8)**	**(83.6)**
Products in Use	(54.8)	(42.6)	(30.4)	(34.9)	(29.0)	(24.4)	(20.0)
SWDS	(69.0)	(63.4)	(64.8)	(65.3)	(65.1)	(64.5)	(63.6)
Total Net Flux	**(774.0)**	**(687.3)**	**(725.6)**	**(688.3)**	**(677.1)**	**(634.8)**	**(668.1)**

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-20 and 6-21 for non-CO_2 emissions from drainage of organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Notes: Forest ecosystem C stock changes do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 6-9: Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Forest Ecosystem	**(177.3)**	**(158.5)**	**(171.9)**	**(160.4)**	**(159.0)**	**(148.9)**	**(159.4)**
Aboveground Biomass	(126.1)	(113.5)	(118.0)	(111.2)	(110.9)	(107.2)	(108.7)
Belowground Biomass	(25.7)	(23.0)	(23.5)	(22.1)	(22.0)	(21.3)	(21.6)
Dead Wood	(26.4)	(26.4)	(29.0)	(27.2)	(27.8)	(26.5)	(27.7)
Litter	0.2	4.4	(0.9)	(0.5)	0.3	6.2	(0.5)
Soil (Mineral)	0.8	(0.1)	(1.5)	(0.3)	1.1	(0.2)	(1.1)
Soil (Organic)	(0.3)	(0.1)	0.8	0.7	0.1	(0.2)	0.1
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.9)**	**(27.3)**	**(25.7)**	**(24.2)**	**(22.8)**
Products in Use	(14.9)	(11.6)	(8.3)	(9.5)	(7.9)	(6.6)	(5.5)
SWDS	(18.8)	(17.3)	(17.7)	(17.8)	(17.8)	(17.6)	(17.3)
Total Net Flux	**(211.1)**	**(187.4)**	**(197.9)**	**(187.7)**	**(184.7)**	**(173.1)**	**(182.2)**

[a] These estimates include carbon stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the C flux from drained organic soils. Also, see Table 6-20 and 6-21 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Notes: Forest ecosystem C stock changes do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood C storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil C pools account for a large proportion of total forest ecosystem C stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6.1 Representation of the U.S. Land Base for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-10 only include managed forest land in the conterminous 48 states and Alaska while the area estimates in Section 6.1 include all managed forest land in Hawaii. Differences also exist because forest land area estimates are based on the latest NFI data through 2020 and woodland areas previously included as forest land have been separated and included in the Grassland categories in this Inventory.[32]

Table 6-10: Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	2005	2017	2018	2019	2020	2021
Forest Area (1,000 ha)	***282,585***	***282,250***	***282,352***	***282,312***	***282,177***	***282,061***	***281,951***
Carbon Pools (MMT C)							
Forest Ecosystem	**53,148**	**55,721**	**57,687**	**57,848**	**58,007**	**58,156**	**58,316**
Aboveground Biomass	12,062	13,874	15,250	15,361	15,472	15,579	15,688
Belowground Biomass	2,375	2,743	3,019	3,041	3,064	3,085	3,106
Dead Wood	2,060	2,460	2,787	2,814	2,842	2,868	2,896
Litter	3,838	3,834	3,815	3,816	3,815	3,809	3,810
Soil (Mineral)	25,458	25,452	25,458	25,458	25,457	25,457	25,459
Soil (Organic)	7,355	7,358	7,357	7,357	7,357	7,357	7,357
Harvested Wood	**1,895**	**2,353**	**2,618**	**2,645**	**2,671**	**2,695**	**2,718**
Products in Use	1,249	1,447	1,506	1,515	1,523	1,530	1,536
SWDS	646	906	1,112	1,129	1,147	1,165	1,182
Total C Stock	**55,043**	**58,074**	**60,305**	**60,493**	**60,678**	**60,851**	**61,034**

Notes: Forest area and C stock estimates include all *Forest Land Remaining Forest Land* in the conterminous 48 states and Alaska. Forest ecosystem C stocks do not include forest stocks in U.S. Territories because managed forest land for U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stocks do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. Population estimates compiled using FIA data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, an estimate of flux for 2020 requires estimates of C stocks for 2020 and 2021.

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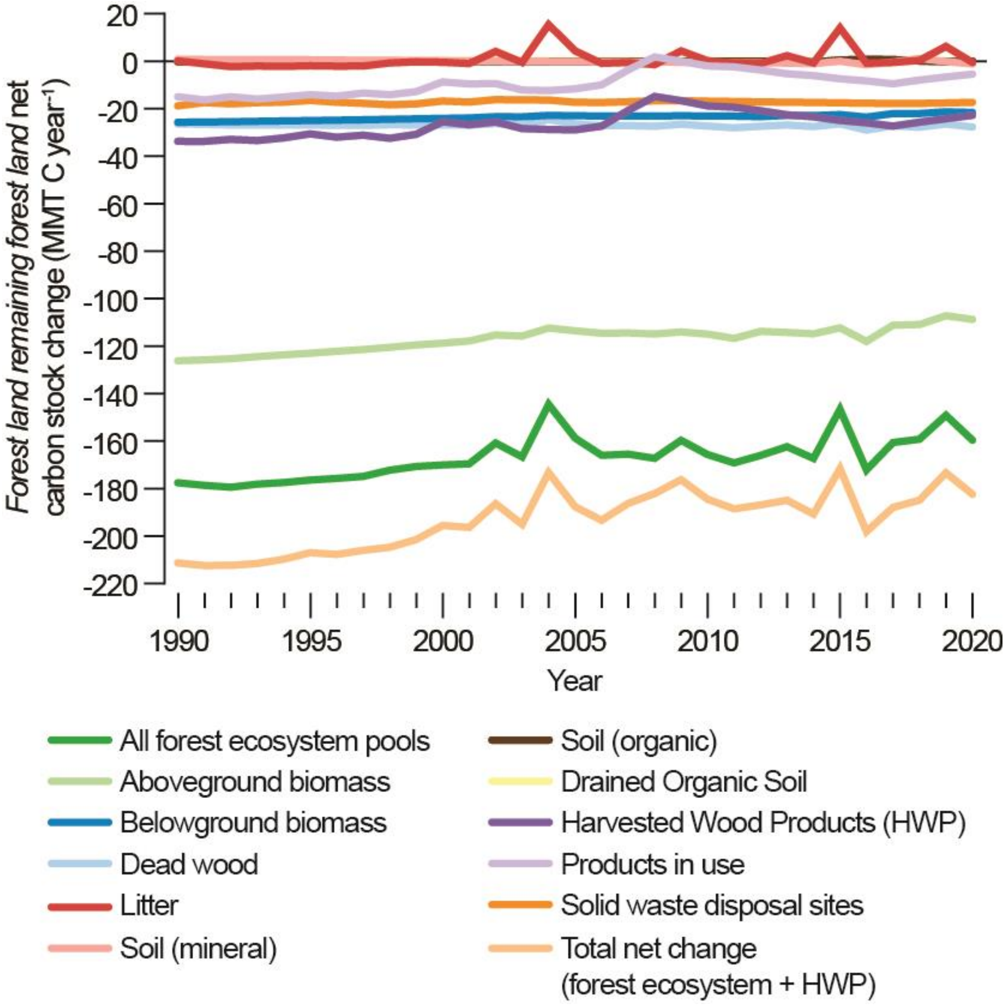
[32] See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in C Stocks for All C Pools in *Forest Land Remaining Forest Land* in the Conterminous United States and Alaska (1990-2020)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all C losses due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and UNFCCC reporting requirements.

Emissions estimates are developed consistent with IPCC (2006) methodology and based on U.S.-specific data and models to quantify the primary fire-specific components: area burned; availability and combustibility of fuel: fire severity (or consumption); and CO_2 and non-CO_2 emissions. Estimated CO_2 emissions for fires on forest lands in the conterminous 48 states and in Alaska for 2020 are 237 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest C stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimate CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with C stock change estimates provided above.

Table 6-11: Estimates of CO2 (MMT per Year) Emissions from Forest Fires in the Conterminous 48 States and Alaska[a]

Year	CO_2 emitted from fires on forest land in the Conterminous 48 States (MMT yr^{-1})	CO_2 emitted from fires on forest land in Alaska (MM Tyr^{-1})	Total CO_2 emitted (MMTyr^{-1})
1990	11.2	26.0	**37.1**
2005	33.9	93.5	**127.4**
2016	73.1	5.7	**78.8**
2017	154.8	10.0	**164.8**
2018	108.5	6.7	**115.2**
2019	27.0	55.8	**82.7**
2020	236.8	0.6	**237.4**

[a] These emissions have already been included in the estimates of net annual changes in C stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate C stocks and net annual C stock changes in Alaska. The approaches for estimating carbon stocks and stock changes on *Forest Land Remaining Forest Land* are described in Annex 3.13. All annual NFI plots available in the public FIA database (USDA Forest Service 2022b) were used in the current Inventory. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this report as were plots established and measured since 2015 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6.1 Representation of the U.S. Land Base) are measured in the NFI, as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ with the other land use categories where area estimates reported in the Land Representation were not updated (see Section 6.1 Representation of the U.S. Land Base) Further, HI was not included in this section of the current Inventory so that also contributes to small differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base (See Annex 3.13 for details on differences). To implement the stock-difference approach, forest Land conditions in the CONUS were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2020. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation. To implement the gain-loss approach in Alaska, forest land conditions in Alaska were observed on NFI plots from 2004 to 2020. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2020. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all base intensity NFI plot locations (representing approximately 2,403 ha) in coastal southeast and southcentral Alaska and for 1/5 intensity plots in interior Alaska (representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses by forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2020. To estimate C stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems within the conterminous states and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 and Domke et al. (In prep) for details and additional information related to the methods and data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current Inventory which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures and enables the delineation of forest C accumulation by forest growth, land use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest C to disturbances and delineates *Land Converted to Forest Land* from *Forest Land Remaining Forest Land*. As part of this development, C pool science will continue and will be expanded to improve the estimates of C stock transfers from forest land to other land uses and include techniques to better identify land use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2022a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; USDA Forest Service 2022d, 2022a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five-panel design, with 20 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically 10 percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual inventory datasets by state. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as “moving window” averages, which mean that a portion—but not all—of the previous year’s inventory is updated each year (USDA Forest Service 2022d). Forest C estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five C storage pools identified by IPCC (2006) and described above. All estimates were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2022b, 2022c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. If inventory plots included data on individual trees, aboveground and belowground (coarse roots) tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of tree volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total carbon stocks or stock changes across all forest ecosystem C pools each year.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models as described below. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Carbon in Forest Soil

Soil carbon is the largest terrestrial C sink with much of that C in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O’Neill et al. 2005). Observations of mineral and organic soil C on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a modeling approach that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil C to a depth of 100 cm from empirical measurements to a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil C stocks specific to forest land in the United States (Domke et al. 2017). This new approach allowed for separation of mineral and organic soils, the latter also referred to as Histosols, in the *Forest Land Remaining Forest Land* category. Note that mineral and organic (i.e., undrained organic soils) soil C stock changes are reported to a depth of 100 cm for *Forest Land Remaining Forest Land* to remain consistent with past reporting in this category, however for consistency across land-use categories mineral (e.g., cropland, grassland, settlements) soil C is reported to a depth of 30 cm in Section 6.3 *Land Converted to Forest Land*. Estimates of C stock changes from organic soils shown in Table 6-8 and Table 6-9 include separately the emissions from drained organic forest soils, the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in the estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The C loss from harvest is reported in the Forest Ecosystem component of the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* sections and for information purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3). EPA includes HWP within the forest chapter because that is the source of wood that goes into the HWP estimates. EPA includes HWP within the forest chapter because that is the source of wood that goes into the HWP estimates.

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-214 for state-level uncertainties). A Monte Carlo Stochastic Simulation of the methods described above, and probabilistic sampling of C conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2020 net annual change for forest C stocks was estimated to be between -744.6 and -592.2 MMT CO_2 Eq. around a central estimate of -668.1 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of -657.5 to -511.4 MMT CO_2 Eq. around a central estimate of -584.4 MMT CO_2 Eq. for forest ecosystems and -106.4 to -63.1 MMT CO_2 Eq. around a central estimate of -83.6 MMT CO_2 Eq. for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO_2	(584.4)	(657.5)	(511.4)	-12.5%	12.5%
Harvested Wood Products[b]	CO_2	(83.6)	(106.4)	(63.1)	-27.3%	24.5%
Total Forest	**CO_2**	**(668.1)**	**(744.6)**	**(592.2)**	**-11.5%**	**11.4%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Notes: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2022d).

General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2022b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from U.S. Census and USDA Forest Service surveys of production and trade and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; FAO 2021). Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

The methods used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes and HWPs from 1990 through 2020 are consistent with those used in the previous (1990 through 2019) Inventory. Population estimates of carbon stocks and stock changes were compiled using NFI data from each U.S. state and national estimates were compiled by summing over all states. New NFI data in most states were incorporated in the latest Inventory which contributed to increases in forest land area estimates and carbon stocks, particularly in Alaska where new data from 2018 to 2020 (with the exception of litter and soil) were included (Table 6-13). Fire data sources were also updated for AK through 2020 and this combined with the new NFI data for the years 2018 through 2020 resulted in substantial changes in carbon stocks and stock changes. In 2019, in particular, an estimated 646,276 ha of forest land burned in AK—the fifth largest fire year in the time-series— which resulted in substantial differences in the carbon stock and stock change estimates reported in the previous (i.e., 1990 through 2019) Inventory and those in the current Inventory. Additionally, this report does not include separate emission estimates for prescribed fires (a change from recent annual reports) because the data records do not specify the fire origins allowing for separation of wild and prescribed fire emissions. Soil carbon stocks increased in the latest Inventory relative to the previous Inventory and this change can be attributed to refinements in the Digital General Soil Map of the United States (STATSGO2) dataset where soil orders may have changed in the updated data product (Table 6-13). This resulted in a structural change in the soil organic carbon estimates for mineral and organic soils across the entire time series, particularly in AK where new data on forest area was included for the years 2018 through 2020 (Table 6-8). Finally, recent land use change in AK (since 2015) also contributed to variability in soil carbon stocks and stock changes in recent years in the time series which contributed to differences in estimates in the 2021 Inventory and the current Inventory. New data in the HWP time-series result in a minor decrease (< 1 percent) in carbon stocks in the HWP pools but a substantial decrease (38 percent) in the carbon stock change estimates for Products in Use and to a lesser extent (7 percent) in SWDS between the previous Inventory and the current Inventory. The new HWP data suggest a continued decline in paper products in use over time due to changes in consumer behavior (i.e., more use of electronic information sources) and a small drop in solid wood products in the last year due to a downturn in the economy associated with the global pandemic.

Table 6-13: Recalculations of Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	2020 Estimate, Previous Inventory	2020 Estimate, Current Inventory	2021 Estimate, Current Inventory
Forest Area (1000 ha)	***279,289***	***282,061***	***281,951***
Carbon Pools (MMT C)			
Forest	**55,933**	**58,156**	**58,316**
Aboveground Biomass	15,260	15,579	15,688
Belowground Biomass	3,103	3,085	3,106

Dead Wood	2,852	2,868	2,896
Litter	3,638	3,809	3,810
Soil (Mineral)	25,147	25,457	25,459
Soil (Organic)	5,933	7,357	7,357
Harvested Wood	**2,699**	**2,695**	**2,718**
Products in Use	1,532	1,530	1,536
SWDS	1,167	1,165	1,182
Total Stock	**58,632**	**60,851**	**61,034**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2019 Estimate, Previous Inventory	2019 Estimate, Current Inventory	2020 Estimate, Current Inventory
Forest	**(159.1)**	**(148.9)**	**(159.4)**
Aboveground Biomass	(107.4)	(107.2)	(108.7)
Belowground Biomass	(24.3)	(21.3)	(21.6)
Dead Wood	(27.1)	(26.5)	(27.7)
Litter	(0.1)	6.2	(0.5)
Soil (Mineral)	(0.7)	(0.2)	(1.1)
Soil (Organic)	0.3	(0.2)	0.1
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(29.6)**	**(24.2)**	**(22.8)**
Products in Use	(10.7)	(6.6)	(5.5)
SWDS	(18.9)	(17.6)	(17.3)
Total Net Flux	**(188.7)**	**(173.1)**	**(182.2)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

Reliable estimates of forest C stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual Inventory submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual C pool estimation, coordination with other land-use categories, and annual inventory data incorporation.

While this Inventory submission includes C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* and C stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the CONUS in the current Inventory for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land use categories in the current Inventory, research is underway to leverage all FIA data and auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, and disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI, but not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which will eliminate latency in population estimates from the NFI, improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for easier harmonization of NFI data with auxiliary data products. This will also facilitate separation of prescribed and wildfire emissions in future reports. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open source code (e.g., R programming language) in concert with the public availability of the annual NFI (USDA Forest Service 2022b). Also, several FIA database processes are being institutionalized to increase efficiency and

QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches were used to estimate uncertainty associated with C stock changes in the *Forest Land Remaining Forest Land* category in this report. There is research underway investigating more robust approaches to total uncertainty (Clough et al. 2016), which will be considered in future Inventory reports.

The modeling framework used to estimate downed dead wood within the dead wood C pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil C pools (Domke et al. 2017). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized in the Inventory report.

The foundation of forest C estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2022b). With the exception of Wyoming and western Oklahoma, all other states in the CONUS now have sufficient annual NFI data to consistently estimate C stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in Alaska as part of the operational NFI and as more plots are added to the NFI they will be used to improve estimates for all managed forest land in Alaska. The methods used to include all managed forest land in Alaska will be used in the years ahead for Hawaii and U.S. Territories as forest C data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid not only the interior Alaska effort but the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) as this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land use category (e.g., woodlands, which fall into the grasslands land use category, and urban areas, which fall into the settlements land use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data and models for annual area of forest burned, fuel, consumption, and emission consistent with IPCC (2006). In 2020, emissions from this source were estimated to be 13.7 MMT CO_2 Eq. of CH_4 and 11.7 MMT CO_2 Eq. of N_2O (Table 6-15; kt units provided in Table 6-16). The estimates of non-CO_2 emissions from forest fires are for the conterminous 48 states and all managed forest land in Alaska (Ogle et al. 2018).

Table 6-15: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990		2005		2016	2017	2018	2019	2020
CH_4	2.3		6.5		3.9	9.5	6.2	1.1	13.6
N_2O	1.8		6.3		3.9	8.2	5.7	1.3	11.7
Total	**4.1**		**12.8**		**7.8**	**17.7**	**11.9**	**2.5**	**25.3**

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Totals may not sum due to independent rounding

Table 6-16: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990		2005		2016	2017	2018	2019	2020

CH_4	92		260		154	381	249	45	545
N_2O	6		21		13	27	19	4	39
CO	2,589		7,284		3,775	8,591	5,457	1,095	11,739
NO_x	47		120		87	167	119	30	224

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Methodology and Time-Series Consistency

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated consistent with IPCC (2006) methodology, which included U.S.-specific data and models on area, fuel, consumption, and emission. The annual estimates were calculated by the Wildland Fire Emissions Inventory System (WFEIS, French et al. 2011, 2014) with area burned based on Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007) or MODIS burned area mapping (MODIS MCD64A1, Giglio et al. 2018) data. The MTBS data available for this report (MTBS 2021) included fires through 2018 with only a partial set of the 2019 fires included with the data. The MODIS-based records include 2001 through 2020. Emissions reported here originate from MTBS data for the 1990 to 2018 interval, and the 2019 and 2020 emissions are based on MODIS burned areas. All other parts of calculations—fuels, fire characteristics, and emissions—are via WFEIS and therefore identical throughout the 1990 to 2020 interval. Note that N_2O emissions are not included in WFEIS calculations; the emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 following Larkin et al. (2014). See Emissions from Forest Fires in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

In order to quantify the uncertainties for non-CO_2 emissions from forest fires, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainties in per-fire quantities of fuel and forest area burned. See Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-17.

Table 6-17: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	**Gas**	**2020 Emission Estimate (MMT CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Non-CO_2 Emissions from Forest Fires	CH_4	13.6	8.6	19.3	-37%	42%
Non-CO_2 Emissions from Forest Fires	N_2O	11.7	7.6	16.3	-35%	39%

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process and results were consistent with values expected from those calculations. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2020) Inventory to compile estimates of non-CO_2 emissions from forest fires represent a change relative to the previous (1990 through 2019) Inventory. The basic components of calculating forest fire emissions (IPCC 2006) remain unchanged, but the WFEIS-based estimates for fuel, combustion, and allocation of emissions provide both increased specificity (for site and fire) and more consistent application of these factors. An additional source of change recalculation are recent updates to the MTBS fire records (post-2000 fires). These recalculations resulted in a 10 percent increase in average annual emissions over the 2014 to 2018 interval as compared to the previous Inventory (interval represents years with emissions estimated via both past and current methods for comparison).

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires. The focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty, and identification of forest area burned but not included in the MTBS records.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia [NH_3] and nitrogen oxide [NO_x], in addition to leaching and runoff of nitrates [NO_3], and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*[33] in 2020 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2020 were 0.5 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2020. Total forest soil N_2O emissions are summarized in Table 6-18.

Table 6-18: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2016	2017	2018	2019	2020
Direct N_2O Fluxes from Soils							
MMT CO_2 Eq.	0.1	0.3	0.3	0.3	0.3	0.3	0.3
kt N_2O	+	1.2	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils							
MMT CO_2 Eq.	+	0.1	0.1	0.1	0.1	0.1	0.1
kt N_2O	+	+	+	+	+	+	+
Total							
MMT CO_2 Eq.	**0.1**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N_2O	**+**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 kt.

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[33] The N_2O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

Note: Totals may not sum due to independent rounding. The N_2O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

Methodology and Time-Series Consistency

The IPCC Tier 1 approach is used to estimate N_2O from soils within *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2020, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2020, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

The same method is applied in all years of this Inventory to ensure time-series consistency from 1990 through 2020.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic N fertilizers to forest are captured in this inventory, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils in the United States is included in the inventory for Agricultural Soil Management (Section 5.4) and *Settlements Remaining Settlements* (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2004 activity data and emission factor input variables are directly applied to the 2020 emission estimates. IPCC (2006)

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[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-19. Direct N_2O fluxes from soils in 2020 are estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2020. Indirect N_2O emissions in 2020 are 0.1 MMT CO_2 Eq. and have a range are between 0.02 and 0.4 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2020.

Table 6-19: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.1	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.4	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data.

Recalculations Discussion

No recalculations were performed for the 1990 to 2019 estimates.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2022b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current Inventory. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2022b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly

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[35] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2022c, d) are labeled “drained organic soil” sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2020 are estimated as 0.8 MMT CO_2 Eq. per year (Table 6-20; kt units provided in 6-21).

The Tier 1 methodology provides methods to estimate C emission as CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-20: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-21: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990	2005	2016	2017	2018	2019	2020
CH_4	1	1	1	1	1	1	1
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Methodology and Time-Series Consistency

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2022d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-22).

Table 6-22: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of C emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway—indirect, or off-site, emissions—is associated with dissolved organic carbon releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of dissolved organic carbon (DOC) from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway—emissions from (peat) fires on organic soils—assumes that the drained organic soils burn in a fire but not any wet organic soils. However, this Inventory currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current Inventory, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Methodological calculations were applied to the entire set of estimates for 1990 through 2020. Year-specific data are not available. Estimates are based on a single year and applied as the annual estimates over the interval.

Uncertainty

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-23). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this inventory, which results in minor changes in the less significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2020 from drained organic soils on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* were estimated to be between -0.006 and 0.162 MMT CO_2 Eq. around a central estimate of 0.073 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-23: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-69%	+82%
N_2O	0.1	+	0.1	-118%	+132%
Total	**0.1**	**+**	**0.2**	**-109%**	**+123%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic C from drainage waters may be double counted if soil C stock and change is based on sampling and this C is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the Wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 estimates.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports are made available and new geospatial products become available.

6.3 Land Converted to Forest Land (CRF Source Category 4A2)

The C stock change estimates for *Land Converted to Forest Land* that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as *Forest Land Remaining Forest Land*. Estimates of C stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the *Land Converted to Forest Land* category of this Inventory.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout U.S. history. The 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., Cropland, Grassland, Wetlands, Settlements, and Other Lands) to Forest Land resulted in a fairly continuous net annual accretion of Forest Land area from over the time series at an average rate of 1.0 million ha year^{-1}.

Over the 20-year conversion period used in the *Land Converted to Forest Land* category, the conversion of cropland to forest land resulted in the largest source of C transfer and uptake, accounting for approximately 40 percent of the uptake annually. Estimated C uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of C from all forest pool stock changes in 2020 was -99.5 MMT CO_2 Eq. (-27.1 MMT C) (Table 6-24 and Table 6-25).

Mineral soil C stocks increase slightly over the time series for Land Converted to Forest Land. The small gains are associated with Cropland Converted to Forest Land, Settlements Converted to Forest Land, and Other Land Converted to Forest Land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil C. In contrast, Grassland Converted to Forest Land leads to a loss of soil C across the time series, which negates some of the gain in soil C with the other land use conversions. Managed pasture to Forest Land is the most common conversion. This conversion leads to a loss of soil C because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances C input to soils relative to typical forest management activities.

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[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversion to forest in Alaska and Hawaii were not included. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 Land Converted to Forest Land.

Table 6-24: Net CO_2 Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Forest Land	**(39.6)**	**(39.5)**	**(39.5)**	**(39.6)**	**(39.6)**	**(39.6)**	**(39.6)**
Aboveground Biomass	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)
Belowground Biomass	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)
Dead Wood	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Litter	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)
Mineral Soil	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Grassland Converted to Forest Land	**(11.5)**	**(11.6)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Aboveground Biomass	(5.9)	(6.0)	(6.1)	(6.1)	(6.1)	(6.1)	(6.1)
Belowground Biomass	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(3.8)	(3.8)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)
Mineral Soil	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Other Land Converted to Forest Land	**(10.1)**	**(10.7)**	**(10.9)**	**(10.9)**	**(10.9)**	**(10.9)**	**(10.9)**
Aboveground Biomass	(4.7)	(4.8)	(4.9)	(4.9)	(4.9)	(4.9)	(4.9)
Belowground Biomass	(0.8)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Litter	(2.5)	(2.5)	(2.6)	(2.6)	(2.6)	(2.6)	(2.6)
Mineral Soil	(0.6)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Settlements Converted to Forest Land	**(34.2)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**
Aboveground Biomass	(20.9)	(20.9)	(20.8)	(20.8)	(20.8)	(20.8)	(20.8)
Belowground Biomass	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)
Dead Wood	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)
Litter	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Mineral Soil	(0.1)	(0.04)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(55.9)**	**(55.9)**	**(56.1)**	**(56.1)**	**(56.1)**	**(56.1)**	**(56.1)**
Total Belowground Biomass Flux	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**
Total Dead Wood Flux	**(11.7)**	**(11.7)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Total Litter Flux	**(19.8)**	**(19.8)**	**(19.9)**	**(19.9)**	**(19.9)**	**(19.9)**	**(19.9)**
Total Mineral Soil Flux	**(0.8)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**
Total Flux	**(98.6)**	**(99.1)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the Forest Land Remaining Forest Land section because there is insufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is insufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for all organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

Table 6-25: Net C Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Forest Land	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**
Aboveground Biomass	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)
Belowground Biomass	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Dead Wood	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Litter	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)
Mineral Soil	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(3.1)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.6)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(1.0)	(1.0)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Mineral Soil	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.7)**	**(2.9)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soil	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**
Aboveground Biomass	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)
Belowground Biomass	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Mineral Soil	+	+	+	+	+	+	+
Wetlands Converted to Forest Land	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.2)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**
Total Belowground Biomass Flux	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**
Total Dead Wood Flux	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Total Litter Flux	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**
Total Mineral Soil Flux	**(0.2)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Total Flux	**(26.9)**	**(27.0)**	**(27.1)**	**(27.1)**	**(27.1)**	**(27.1)**	**(27.1)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the *Forest Land Remaining Forest Land* section because there is not sufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. National Forest Inventory data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools. Estimates for Aboveground and Belowground Biomass, Dead Wood and Litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2022b, 2022c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the *Land Converted to Forest Land* are consistent with those used for *Forest Land Remaining Forest Land*. For land use conversion, IPCC (2006) default biomass C stocks removed due to land use conversion from Croplands and Grasslands were used in the year of conversion on individual plots. All annual NFI plots available through August 2021 were used in this Inventory. Forest Land conditions were observed on NFI plots at time t_0 and at a subsequent time t_1=t_0+s, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2020. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, above- and belowground tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from Grassland and Cropland to Forest Land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on Grasslands and aboveground biomass on Croplands were subtracted from sequestration in the year of the conversion. For all other land use (i.e., Other Lands, Settlements, Wetlands) conversions to Forest Land no biomass loss data were available, and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion, so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). See Annex 3.12 (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management) for more information about this method. Note that soil C in this Inventory is reported to a depth of 100 cm in the Forest Land Remaining Forest Land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006), as described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Mineral soil organic C stock changes from 2016 to 2020 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2016 to 2020 emissions in a future Inventory.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for *Land Converted to Forest Land* through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool C stock changes were developed using the same methodologies as described in the *Forest Land Remaining Forest Land* section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference C stocks in certain conversion categories (i.e., *Cropland Converted to Forest Land* and *Grassland Converted to Forest Land*). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used for mineral soils and is described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-26 for each land conversion category and C pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil C pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all C stocks in *Land Converted to Forest Land* ranged from 11 percent below to 11 percent above the 2020 C stock change estimate of -99.5 MMT CO_2 Eq.

Table 6-26: Quantitative Uncertainty Estimates for Forest C Pool Stock Changes (MMT CO_2 Eq. per Year) in 2020 from *Land Converted to Forest Land* by Land Use Change

Land Use/Carbon Pool	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	**(39.6)**	**(48.2)**	**(30.9)**	**-22%**	**22%**
Aboveground Biomass	(23.0)	(31.4)	(14.5)	-37%	37%
Belowground Biomass	(4.4)	(5.5)	(3.4)	-24%	24%
Dead Wood	(5.0)	(6.2)	(3.8)	-24%	24%
Litter	(6.9)	(8.0)	(5.8)	-16%	16%
Mineral Soils	(0.2)	(0.5)	0.1	-134%	134%
Grassland Converted to Forest Land	**(11.8)**	**(14.3)**	**(9.4)**	**-21%**	**20%**
Aboveground Biomass	(6.1)	(7.5)	(4.7)	-23%	23%
Belowground Biomass	(1.0)	(1.3)	(0.7)	-28%	28%
Dead Wood	(1.1)	(1.3)	(1.0)	-13%	13%
Litter	(3.9)	(4.4)	(3.4)	-14%	14%
Mineral Soils	0.3	(0.1)	0.6	-136%	136%
Other Lands Converted to Forest Land	**(10.9)**	**(13.2)**	**(8.5)**	**-22%**	**22%**
Aboveground Biomass	(4.9)	(7.0)	(2.8)	-43%	43%
Belowground Biomass	(0.9)	(1.3)	(0.4)	-50%	50%
Dead Wood	(1.4)	(2.0)	(0.8)	-40%	40%
Litter	(2.6)	(3.2)	(2.0)	-25%	25%
Mineral Soils	(1.1)	(1.9)	(0.4)	-66%	66%
Settlements Converted to Forest Land	**(34.1)**	**(40.6)**	**(27.6)**	**-19%**	**19%**
Aboveground Biomass	(20.8)	(27.0)	(14.6)	-30%	30%
Belowground Biomass	(4.0)	(5.3)	(2.7)	-33%	33%
Dead Wood	(3.9)	(5.0)	(2.7)	-30%	30%
Litter	(5.3)	(6.2)	(4.4)	-17%	17%
Mineral Soil	(0.1)	(0.1)	+	-44%	44%
Wetlands Converted to Forest Land	**(3.2)**	**(3.4)**	**(3.0)**	**-5%**	**5%**
Aboveground Biomass	(1.4)	(1.5)	(1.2)	-10%	10%
Belowground Biomass	(0.3)	(0.3)	(0.2)	-12%	12%
Dead Wood	(0.4)	(0.4)	(0.3)	-11%	11%
Litter	(1.2)	(1.3)	(1.1)	-5%	5%
Mineral Soils	0.0	0.0	0.0	NA	NA
Total: Aboveground Biomass	**(56.1)**	**(66.9)**	**(45.4)**	**-19%**	**19%**
Total: Belowground Biomass	**(10.5)**	**(12.3)**	**(8.8)**	**-17%**	**17%**
Total: Dead Wood	**(11.8)**	**(13.6)**	**(10.0)**	**-15%**	**15%**
Total: Litter	**(19.9)**	**(21.6)**	**(18.4)**	**-8%**	**8%**
Total: Mineral Soils	**(1.1)**	**(1.7)**	**(0.6)**	**-50%**	**50%**
Total: Lands Converted to Forest Lands	**(99.5)**	**(110.7)**	**(88.3)**	**-11%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

QA/QC and Verification

See QA/QC and Verification sections under *Forest Land Remaining Forest Land* and for mineral soil estimates *Cropland Remaining Cropland.*

Recalculations Discussion

The approach for estimating carbon stock changes in *Land Converted to Forest Land* is consistent with the methods used for *Forest Land Remaining Forest Land* and is described in Annex 3.13. The *Land Converted to Forest Land* estimates in this Inventory are based on the land use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass C stocks removed from Croplands and Grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil C stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots available through August 2020 were used in this Inventory. This is the third year that remeasurement data from the annual NFI were available throughout the CONUS (with the exception of Wyoming and western Oklahoma) to estimate land use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of C stocks and stock changes for *Forest Land Remaining Forest Land* and the *Land Converted to Forest Land* categories. Estimates in the previous Inventory were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this Inventory resulted in changes in the *Land Converted to Forest Land* categories. Overall, the *Land Converted to Forest Land* C stock changes decreased by less than 1 percent in 2019 between the previous Inventory and the current Inventory (Table 6-27). This decrease is directly attributed to the incorporation of annual NFI data into the compilation system. In the previous Inventory, *Grasslands Converted to Forest* Land represented the largest transfer and uptake of C across the land use conversion categories. In this Inventory, *Cropland Converted to Forest Land* represented the largest transfer and uptake of C across the land use change categories followed by *Settlements Converted to Forest Land* (Table 6-27).

Table 6-27: Recalculations of the Net C Flux from Forest C Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2019 Estimate, Previous Inventory	2019 Estimate, Current Inventory	2020 Estimate, Current Inventory
Cropland Converted to Forest Land	**(10.9)**	**(10.8)**	**(10.8)**
Aboveground Biomass	(6.3)	(6.3)	(6.3)
Belowground Biomass	(1.2)	(1.2)	(1.2)
Dead Wood	(1.4)	(1.4)	(1.4)
Litter	(1.9)	(1.9)	(1.9)
Mineral soil	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(2.9)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.3)	(1.7)	(1.7)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.3)	(0.3)
Litter	(1.1)	(1.1)	(1.1)
Mineral soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(3.0)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.4)	(0.4)
Litter	(0.7)	(0.7)	(0.7)
Mineral soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.4)**	**(9.3)**	**(9.3)**
Aboveground Biomass	(5.7)	(5.7)	(5.7)
Belowground Biomass	(1.1)	(1.1)	(1.1)
Dead Wood	(1.1)	(1.1)	(1.1)
Litter	(1.5)	(1.5)	(1.5)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.4)	(0.4)	(0.4)
Belowground Biomass	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)
Litter	(0.3)	(0.3)	(0.3)

Mineral soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(15.3)**	**(15.3)**
Total Belowground Biomass Flux	**(2.9)**	**(2.9)**	**(2.9)**
Total Dead Wood Flux	**(3.2)**	**(3.2)**	**(3.2)**
Total Litter Flux	**(5.6)**	**(5.4)**	**(5.4)**
Total SOC (mineral) Flux	**(0.3)**	**(0.3)**	**(0.3)**
Total Flux	**(27.0)**	**(27.1)**	**(27.1)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

There are many improvements necessary to improve the estimation of carbon stock changes associated with land use conversion to forest land over the entire time series. First, soil C has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. 2017) while other land-use categories (e.g., Grasslands and Croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all mineral soil estimates in the *Land Converted to Forest Land* category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil C to depths of 20, 30, and 100 cm in the Forest Land category using in situ measurements from the Forest Inventory and Analysis program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land use conversion categories and Domke et al. (2017) will be used in the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* categories to ensure consistent reporting across all forest land. Third, due to the 5 to 10-year remeasurement periods within the FIA program and limited land use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRF Category 4B1)

Carbon (C) in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, C storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, C is found in organic and inorganic forms of C, but soil organic C is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic C to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a

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[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the Inventory.

net C stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland Remaining Cropland includes all cropland in an Inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2018a) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

Cropland in Alaska is not included in the Inventory, but is a relatively small amount of U.S. cropland area (approximately 28,700 hectares). Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). This leads to a small discrepancy between the managed area in *Cropland Remaining Cropland* (see Table 6-31 in Planned Improvements for more details on the land area discrepancies) and the cropland area included in the Inventory analysis. Improvements are underway to include croplands in Alaska as part of future C inventories.

Land-use and land management of mineral soils are the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-28 and Table 6-29). In 2020, mineral soils are estimated to sequester 56.2 MMT CO_2 Eq. from the atmosphere (15.3 MMT C). This rate of C storage in mineral soils represents about a 3 percent decrease in the rate since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 32.9 MMT CO_2 Eq. (9.0 MMT C) in 2020, which is a 6 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 23.3 MMT CO_2 Eq. (6.4 MMT C) in 2020.

Table 6-28: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO_2 Eq.)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Mineral Soils	(58.2)		(62.4)		(54.3)	(55.1)	(49.4)	(47.4)	(56.2)
Organic Soils	35.0		33.4		31.6	32.8	32.8	32.9	32.9
Total Net Flux	**(23.2)**		**(29.0)**		**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**	**(23.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

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[39] N_2O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the Inventory.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Table 6-29: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Mineral Soils	(15.9)	(17.0)	(14.8)	(15.0)	(13.5)	(12.9)	(15.3)
Organic Soils	9.5	9.1	8.6	8.9	8.9	9.0	9.0
Total Net Flux	**(6.3)**	**(7.9)**	**(6.2)**	**(6.1)**	**(4.5)**	**(4.0)**	**(6.4)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic C stocks increase in *Cropland Remaining Cropland* largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments. However, there is a decline in the net amount of C sequestration (i.e., 2020 is 0.7 percent less than 1990 for mineral and organic soils), and this decline is due to lower sequestration rates in set-aside lands, less impact of manure amendments and annual crop production with hay and pasture in rotation. Soil organic C losses from drainage of organic soils are relatively stable across the time series with a small decline associated with the land base declining for *Cropland Remaining Cropland* on organic soils since 1990.

The spatial variability in the 2015 annual soil organic C stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of C accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas. In particular, higher rates of net C accumulation in mineral soils occur in the Corn Belt region, which is the region with the largest amounts of conservation tillage, along with moderate rates of CRP enrollment. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

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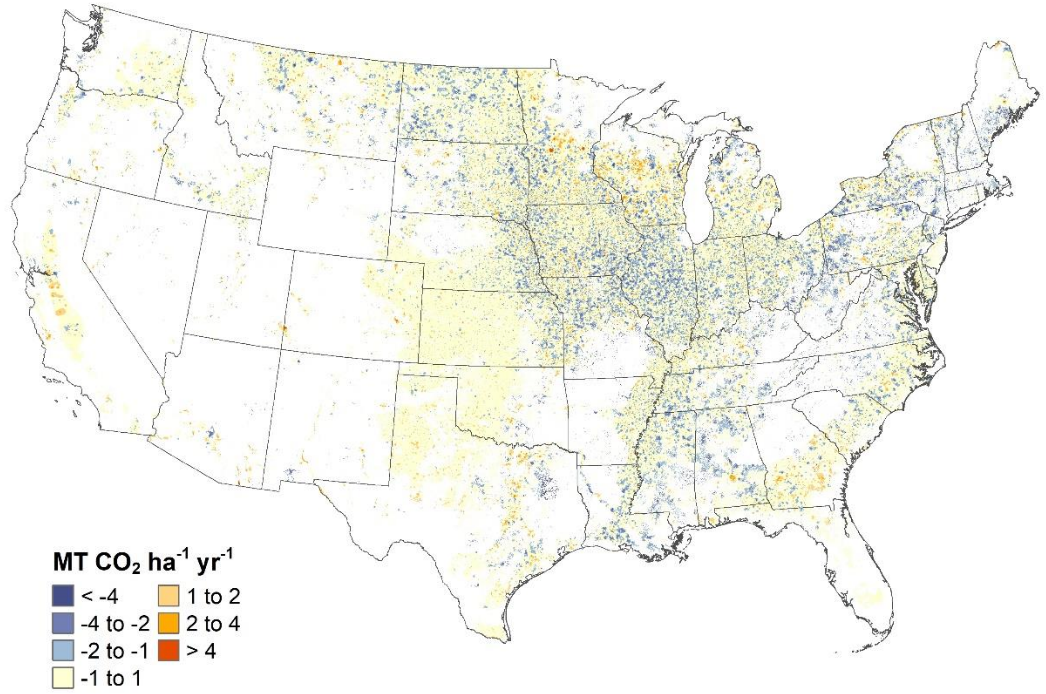
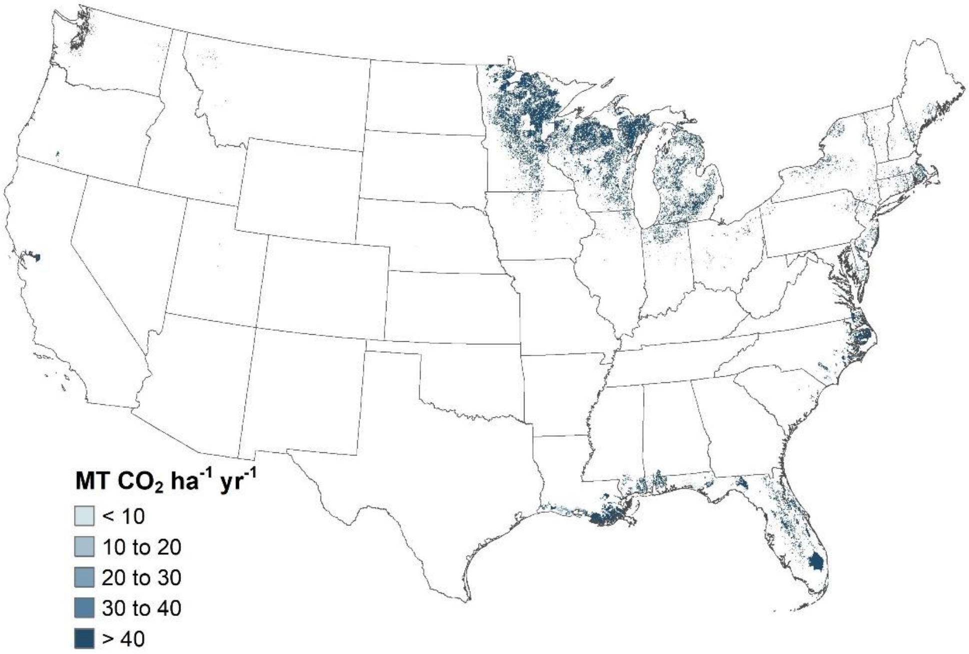
[41] Only national-scale emissions are estimated for 2016 to 2020 in this Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-6: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

Figure 6-7: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic C stocks for *Cropland Remaining Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic C stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate C stock changes across most of the time series, a surrogate data method has been applied to estimate stock changes in the last few years of the Inventory. Stock change estimates based on surrogate data will be recalculated in a future Inventory report using the Tier 2 and 3 methods when data become available.

Soil organic C stock changes on non-federal lands are estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories Land Converted to Cropland, Grassland Remaining Grassland, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2018a). The NRI is a statistically-based sample of all non-federal land, and includes approximately 489,178 survey locations in agricultural land for the conterminous United States and Hawaii. Each survey location is associated with an “expansion factor” that allows scaling of C stock changes from NRI survey locations to the entire country

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[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

(i.e., each expansion factor represents the amount of area that is expected to have the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018a). NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2015 if the land use has been cropland for a continuous time period of at least 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Cropland Remaining Cropland* in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic C stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, but is not applied to estimate organic C stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic C stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and N dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic C stock changes on federal croplands. Mineral soil organic C stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2018). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories with an updated time series of activity data.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic C stock changes in Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland. A linear regression model with autoregressive moving-average

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[43] See https://quickstats.nass.usda.gov/.

(ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2015 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), Xβ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2015 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2016 to 2020.

A critical issue with application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2015), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic C stocks and stock changes are estimated to a 30 cm depth using the DayCent biogeochemical[44] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of C, N, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[45] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2018), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

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[44] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

[45] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2015. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

Box 6-5: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic C stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic C stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic C stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.
2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at about 350,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in C stocks that assumes a step-change from one equilibrium level of the C stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of C stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil organic C stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018a). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. These data are combined with other datasets in an imputation analysis that extend the time series from 1990 to 2015. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information across several datasets (discussed below), b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994), and c) assign management practices from the CEAP survey to the specific NRI locations using predictive mean matching methods that is adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a very large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. Predictive mean matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments from 1979 to 2015, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of a data collection program known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2018). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both rates. This approach captures the relationship between mineral fertilization and manure amendment practices for U.S. croplands based directly on the observed patterns in the CEAP survey data.

To determine the trends in tillage management from 1979 to 2015, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and USDA-ERS Agriculture Resource Management Surveys (ARMS) data from 2002 to 2015 (Claasen et al. 2018). CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). It is assumed that the majority of agricultural lands are managed with full tillage prior to 1985. For cover crops, CEAP data are combined with information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover cropping was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management derived from the CEAP survey.

Uncertainty in the C stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of C and N dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. To assess input uncertainty, the C and N dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator as described in Ogle et al. (2007, 2010). Sampling uncertainty is assessed using the NRI replicate sampling weights.

Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015 using the DayCent model. However, note that the areas have been modified in the original NRI survey through the process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015) are harmonized with the NRI data. This process ensures that the areas of *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* are consistent with other land use categories while maintaining a consistent time series for the total land area of the United States. For example, if the FIA estimate less *Cropland Converted to Forest Land* than the NRI, then the amount of area for this land use conversion is reduced in the NRI dataset and re-classified as *Cropland Remaining Cropland* (See Section 6.1, Representation of the U.S. Land Base for more information). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future inventory, and emissions from 2016 to 2020 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic C stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2015 NRI survey (USDA-NRCS 2018a). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. The one exception are activity data on wetland restoration of Conservation Reserve Program land that are obtained from Euliss and Gleason (2002). Climate zones in the United States are classified using mean precipitation and temperature (1950 to 2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008, 2007) (Figure A-9). IPCC climate zones are then assigned to NRI survey locations.

Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific C stock change factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Changes in soil organic C stocks for mineral soils are estimated 1,000 times for 1990 through 2015, using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2003; Ogle et al. 2006). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future inventory, and emissions from 2016 to 2020 will be recalculated (see Planned Improvements section).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates include a measure of uncertainty as determined from a Monte Carlo Simulation with 1,000 iterations. Emissions are based on the land area data for drained organic soils from 1990 to 2015 for *Cropland Remaining Cropland* in the 2015 NRI (USDA-NRCS 2018a). Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

In order to ensure time-series consistency, the same Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2016 to 2020 will be recalculated in a future inventory when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is quantified for changes in soil organic C stocks associated with *Cropland Remaining Cropland* (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-30 for each subsource (mineral and organic soil C stocks) and the methods that are used in the Inventory analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived using a Monte Carlo approach (see Annex 3.12 for further discussion). For 2016 to 2020, additional uncertainty is propagated through the Monte Carlo Analysis that is associated with the surrogate data method. Soil organic C stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Cropland Remaining Cropland* ranges from 317 percent below to 317 percent above the 2020 stock change estimate of -23.3 MMT CO_2 Eq. The large relative uncertainty around the 2020 stock change estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-30: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(51.4)	(122.4)	19.7	-138%	+138%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(4.9)	(11.9)	2.1	-144%	+144%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	32.9	13.9	51.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(23.3)**	**(97.2)**	**50.5**	**-317%**	**+317%**

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter C stock changes. However, woody biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass C stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the Inventory time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 72 long-term experiment sites and 142 NRI soil monitoring network sites, with 948 observations across all of the sites (see Annex 3.12 for more information).

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A key improvement for a future Inventory will be to incorporate additional management activity data from the USDA-NRCS Conservation Effects Assessment Project survey. This survey has compiled new data in recent years that will be available for the Inventory analysis by next year. The latest land use data will also be incorporated from the USDA National Resources Inventory and related management data from USDA-ERS ARMS surveys.

There are several other planned improvements underway related to the plant production module. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce the bias in model predictions for grasslands, which was discovered through model evaluation by comparing output to measurement data from 72 experimental sites and 142 NRI soil monitoring network sites (See QA/QC and Verification section).

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the Field Burning of Agricultural Residues source category (see Section 5.7). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning.

A review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

In the future, the Inventory will include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data. See Table 6-31 for the amount of managed area in *Cropland Remaining Cropland* that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and also other miscellaneous cropland areas, such as aquaculture.

Many of these improvements are expected to be completed for the 1990 through 2021 Inventory (i.e., 2023 submission to the UNFCCC). However, the timeline may be extended if there are insufficient resources to fund all or part of these planned improvements.

Table 6-31: Area of Managed Land in *Cropland Remaining Cropland* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	162,163	162,134	29
1991	161,721	161,692	29
1992	161,252	161,223	29
1993	159,449	159,420	29
1994	157,732	157,703	29
1995	157,054	157,025	29
1996	156,409	156,380	29
1997	155,767	155,738	29
1998	152,016	151,987	29
1999	151,135	151,105	29
2000	150,981	150,952	29
2001	150,471	150,442	29
2002	150,175	150,146	29
2003	150,843	150,814	29
2004	150,645	150,616	29

2005	150,304	150,275	29
2006	149,791	149,762	29
2007	150,032	150,003	29
2008	149,723	149,694	29
2009	149,743	149,714	29
2010	149,343	149,314	29
2011	148,844	148,815	29
2012	148,524	148,495	29
2013	149,018	148,989	29
2014	149,492	149,463	29
2015	148,880	148,851	29
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and so these years are designated as ND (No data).

6.5 Land Converted to Cropland (CRF Category 4B2)

Land Converted to Cropland includes all cropland in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all croplands in the conterminous United States and Hawaii, but does not include a minor amount of Land Converted to Cropland in Alaska. Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas dynamics in management systems (e.g., aquaculture). Consequently, there is a discrepancy between the total amount of managed area in Land Converted to Cropland (see Section 6.1 Representation of the U.S. Land Base) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and miscellaneous croplands in future C inventories (see Table 6-35 in the Planned Improvements section for more details on the land area discrepancies).

Land-use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use change. All soil organic C stock changes are estimated and reported for Land Converted to Cropland, but reporting of C stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to *Forest* Land Converted to Cropland.[46]

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[46] Changes in biomass C stocks are not currently reported land use conversions to cropland except for Forest Land Converted to Cropland, but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions to cropland, except Forest Land.

Forest Land Converted to Cropland is the largest source of emissions from 1990 to 2020, accounting for approximately 87 percent of the average total loss of C among all of the land use conversions in Land Converted to Cropland. The pattern is due to the large losses of biomass and dead organic matter C for *Forest* Land Converted to Cropland. The next largest source of emissions is Grassland Converted to Cropland accounting for approximately 17 percent of the total emissions (Table 6-32 and Table 6-33).

The net change in total C stocks for 2020 led to CO_2 emissions to the atmosphere of 54.4 MMT CO_2 Eq. (14.8 MMT C), including 28.2 MMT CO_2 Eq. (7.7 MMT C) from aboveground biomass C losses, 5.5 MMT CO_2 Eq. (1.5 MMT C) from belowground biomass C losses, 5.5 MMT CO_2 Eq. (1.5 MMT C) from dead wood C losses, 8.0 MMT CO_2 Eq. (2.2 MMT C) from litter C losses, 3.5 MMT CO_2 Eq. (0.9 MMT C) from mineral soils and 3.8 MMT CO_2 Eq. (1.0 MMT C) from drainage and cultivation of organic soils. Emissions in 2020 are 5 percent higher than emissions in the initial reporting year, i.e., 1990.

Table 6-32: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Land Converted to Cropland by Land Use Change Category (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Grassland Converted to Cropland	**6.9**	**7.5**	**8.5**	**8.7**	**8.5**	**8.4**	**8.8**
Mineral Soils	4.1	4.0	5.2	5.4	5.1	5.1	5.5
Organic Soils	2.7	3.5	3.3	3.3	3.3	3.3	3.3
Forest Land Converted to Cropland	**46.3**	**46.6**	**47.3**	**47.3**	**47.3**	**47.3**	**47.3**
Aboveground Live Biomass	27.4	27.7	28.2	28.2	28.2	28.2	28.2
Belowground Live Biomass	5.3	5.4	5.5	5.5	5.5	5.5	5.5
Dead Wood	5.4	5.4	5.5	5.5	5.5	5.5	5.5
Litter	7.7	7.8	8.0	8.0	8.0	8.0	8.0
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.2
Organic Soils	0.1	0.1	+	+	+	+	+
Other Lands Converted to Cropland	**(2.2)**	**(2.9)**	**(2.1)**	**(2.2)**	**(2.2)**	**(2.3)**	**(2.3)**
Mineral Soils	(2.3)	(2.9)	(2.1)	(2.2)	(2.2)	(2.3)	(2.3)
Organic Soils	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.8**	**0.9**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**
Mineral Soils	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Organic Soils	0.6	0.6	0.3	0.3	0.4	0.4	0.4
Aboveground Live Biomass	**27.4**	**27.7**	**28.2**	**28.2**	**28.2**	**28.2**	**28.2**
Belowground Live Biomass	**5.3**	**5.4**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Dead Wood	**5.4**	**5.4**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Litter	**7.7**	**7.8**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**2.3**	**1.3**	**3.3**	**3.4**	**3.1**	**3.0**	**3.5**
Total Organic Soil Flux	**3.7**	**4.3**	**3.7**	**3.7**	**3.7**	**3.7**	**3.8**
Total Net Flux	**51.8**	**52.0**	**54.1**	**54.3**	**54.0**	**53.9**	**54.4**

\+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-33: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Grassland Converted to Cropland	**1.9**	**2.0**	**2.3**	**2.4**	**2.3**	**2.3**	**2.4**
Mineral Soils	1.1	1.1	1.4	1.5	1.4	1.4	1.5
Organic Soils	0.7	1.0	0.9	0.9	0.9	0.9	0.9
Forest Land Converted to Cropland	**12.6**	**12.7**	**12.9**	**12.9**	**12.9**	**12.9**	**12.9**
Aboveground Live Biomass	7.5	7.6	7.7	7.7	7.7	7.7	7.7
Belowground Live Biomass	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Dead Wood	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Litter	2.1	2.1	2.2	2.2	2.2	2.2	2.2

Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.6)**	**(0.8)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**
Mineral Soils	(0.6)	(0.8)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Organic Soils	+	+	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.3**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**
Mineral Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**7.5**	**7.6**	**7.7**	**7.7**	**7.7**	**7.7**	**7.7**
Belowground Live Biomass	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Dead Wood	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Litter	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**0.6**	**0.4**	**0.9**	**0.9**	**0.8**	**0.8**	**0.9**
Total Organic Soil Flux	**1.0**	**1.2**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Total Net Flux	**14.1**	**14.2**	**14.8**	**14.8**	**14.7**	**14.7**	**14.8**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for Land Converted to Cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic C stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for Forest Land Converted to Cropland. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020). However, there are no country-specific data for cropland biomass, so default biomass values (IPCC 2006) were used to estimate the carbon stocks for the new cropland (litter and dead wood carbon stocks were assumed to be zero since no reference C density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for Land Converted to Cropland according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as Land Converted to Cropland in a given year between 1990 and 2015 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of Land Converted to Cropland in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat. Soil organic C stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2016 to 2020, a surrogate data method is used to estimate soil organic C stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the time series of activity data are updated.

Tier 3 Approach. For the Tier 3 method, mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

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[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[48] See https://quickstats.nass.usda.gov/.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Cropland Remaining Cropland*. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the 2016 to 2020 time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in Land Converted to Cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series (i.e., 2016 to 2020) are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with Forest Land Converted to Cropland is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in *Cropland Remaining Cropland* (Also see Annex 3.12 for further discussion). The uncertainty for annual C emission estimates from drained organic soils in Land Converted to Cropland is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-34 for each subsource (i.e., biomass C stocks, dead wood C stocks, litter C stocks, soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total C stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in Land Converted to Cropland ranged from 95 percent below to 95 percent above the 2020 stock change estimate of 54.4 MMT CO_2 Eq. The large relative uncertainty in the 2020 estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-34: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**8.8**	**(25.5)**	**43.1**	**-390%**	**390%**
Mineral Soil C Stocks: Tier 3	1.1	(33.0)	35.2	-3006%	3,006%
Mineral Soil C Stocks: Tier 2	4.4	1.3	7.4	-70%	70%
Organic Soil C Stocks: Tier 2	3.3	0.8	5.8	-75%	75%
Forest Land Converted to Cropland	**47.3**	**8.8**	**85.8**	**-81%**	**81%**
Aboveground Live Biomass	28.2	(7.6)	64.0	-127%	127%
Belowground Live Biomass	5.5	(1.5)	12.5	-127%	127%
Dead Wood	5.5	(1.5)	12.5	-127%	127%
Litter	8.0	(2.2)	18.2	-127%	143%
Mineral Soil C Stocks: Tier 2	0.2	(0.1)	0.4	-134%	134%
Organic Soil C Stocks: Tier 2	+	(0.1)	0.1	-1852%	1852%
Other Lands Converted to Cropland	**(2.3)**	**(3.7)**	**(0.8)**	**-64%**	**64%**
Mineral Soil C Stocks: Tier 2	(2.3)	(3.7)	(0.8)	-64%	64%
Organic Soil C Stocks: Tier 2	+	+	+	+	+
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	**+**	**-117%**	**117%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	+	-90%	90%
Organic Soil C Stocks: Tier 2	+	+	0.1	-85%	85%
Wetlands Converted to Croplands	**0.6**	**+**	**1.3**	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.5	-107%	107%
Organic Soil C Stocks: Tier 2	0.4	(0.2)	1.0	-142%	142%
Total: Land Converted to Cropland	**54.4**	**2.8**	**106.0**	**-95%**	**95%**
Aboveground Live Biomass	**28.2**	**(7.6)**	**64.0**	**-127%**	**127%**
Belowground Live Biomass	**5.5**	**(1.5)**	**12.5**	**-127%**	**127%**
Dead Wood	**5.5**	**(1.5)**	**12.5**	**-127%**	**127%**
Litter	**8.0**	**(2.2)**	**18.2**	**-127%**	**127%**
Mineral Soil C Stocks: Tier 3	**1.1**	**(33.0)**	**35.2**	**-3006%**	**3,006%**
Mineral Soil C Stocks: Tier 2	**2.3**	**(1.1)**	**5.7**	**-147%**	**147%**
Organic Soil C Stocks: Tier 2	**3.8**	**1.2**	**6.3**	**-68%**	**68%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass C stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter C stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future Inventory.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* for information on QA/QC steps.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in Forest Land Converted to Cropland, and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. As a result, Land Converted to Cropland has an estimated smaller C loss of 0.13 MMT CO_2 Eq. on average over the time series. This represents a 1 percent decrease in C stock changes for *Land Converted to Grassland* compared to the previous Inventory.

Planned Improvements

Planned improvements are underway to include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data that drive C stock changes on long-term cropland. See Table 6-35 for the amount of managed area in Land Converted to Cropland that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and other miscellaneous cropland areas, such as aquaculture. Additional planned improvements are discussed in the Planned Improvements section of *Cropland Remaining Cropland*.

Table 6-35: Area of Managed Land in Land Converted to Cropland that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	**Inventory**	**Not Included in Inventory**
1990	12,308	12,308	<1
1991	12,654	12,654	<1
1992	12,943	12,943	<1
1993	14,218	14,218	<1
1994	15,400	15,400	<1
1995	15,581	15,581	<1
1996	15,888	15,888	<1
1997	16,073	16,073	<1
1998	17,440	17,440	<1
1999	17,819	17,819	<1
2000	17,693	17,693	<1
2001	17,600	17,600	<1
2002	17,487	17,487	<1
2003	16,257	16,257	<1
2004	15,317	15,317	<1
2005	15,424	15,424	<1
2006	15,410	15,410	<1
2007	14,923	14,923	<1
2008	14,399	14,399	<1
2009	13,814	13,814	<1
2010	13,905	13,905	<1
2011	14,186	14,186	<1
2012	14,429	14,429	<1
2013	13,752	13,752	<1
2014	13,050	13,050	<1
2015	13,049	13,049	<1

2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015 so these years are designated as ND (No data).

6.6 Grassland Remaining Grassland (CRF Category 4C1)

Carbon (C) in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of C in grasslands, and have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use and management. C stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic C, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[49]

Grassland Remaining Grassland includes all grassland in an Inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (See Land Representation section for more information about the criteria for forest land). The current Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include approximately 50 million hectares of Grassland Remaining Grassland in Alaska. This leads to a discrepancy with the total amount of managed area in Grassland Remaining Grassland (see Table 6-39 in Planned Improvements for more details on the land area discrepancies) and the grassland area included in the Inventory analysis.

In Grassland Remaining Grassland, there has been considerable variation in C stocks between 1990 and 2020. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total C stocks for 2020 led to net CO_2 emissions to the atmosphere of 4.5 MMT CO_2 Eq. (1.2 MMT C), including 0.2 MMT CO_2 Eq. (0.1 MMT C) from net losses of aboveground biomass C, 0.1 MMT CO_2 Eq. (<0.05 MMT C) from net losses in belowground biomass C, 2.3 MMT CO_2 Eq. (0.6 MMT C) from net losses in dead wood C, 0.2 MMT CO_2 Eq. (0.1 MMT C) from net gains in litter C, 3.3 MMT CO_2 Eq. (0.9 MMT C) from net gains in mineral soil organic C, and 5.4 MMT CO_2 Eq. (1.5 MMT C) from losses of C due to drainage and cultivation of organic soils (Table 6-36 and Table 6-37). Losses of carbon are 35 percent lower in 2020 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2020, with an average annual change of 7.2 MMT CO_2 Eq. (2.0 MMT C).

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[49] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

Table 6-36: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

Soil Type	1990	2005	2016	2017	2018	2019	2020
Aboveground Live Biomass	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Belowground Live Biomass	+	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	2.8	2.7	2.4	2.4	2.4	2.3	2.3
Litter	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Mineral Soils	(2.2)	0.8	0.1	1.4	1.8	4.6	(3.3)
Organic Soils	6.3	5.2	5.4	5.4	5.4	5.4	5.4
Total Net Flux	**6.9**	**8.7**	**8.0**	**9.3**	**9.7**	**12.4**	**4.5**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-37: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Grassland Remaining Grassland (MMT C)

Soil Type	1990	2005	2016	2017	2018	2019	2020
Aboveground Live Biomass	+	+	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	0.8	0.7	0.7	0.7	0.6	0.6	0.6
Litter	+	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.6)	0.2	+	0.4	0.5	1.2	(0.9)
Organic Soils	1.7	1.4	1.5	1.5	1.5	1.5	1.5
Total Net Flux	**1.9**	**2.4**	**2.2**	**2.5**	**2.6**	**3.4**	**1.2**

+ Does not exceed 0.05 MMT C

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

The spatial variability in soil organic C stock changes for 2015[50] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained C in isolated areas that mostly occurred in pastures of the eastern United States. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

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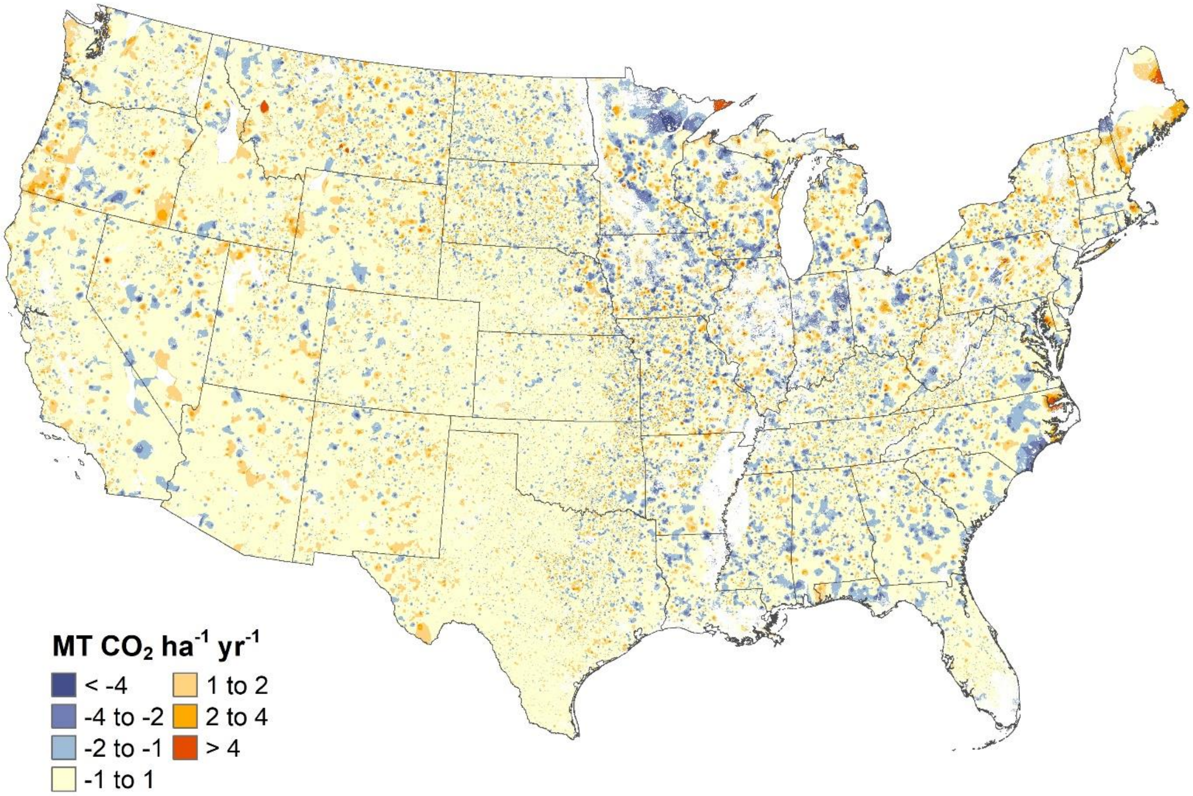
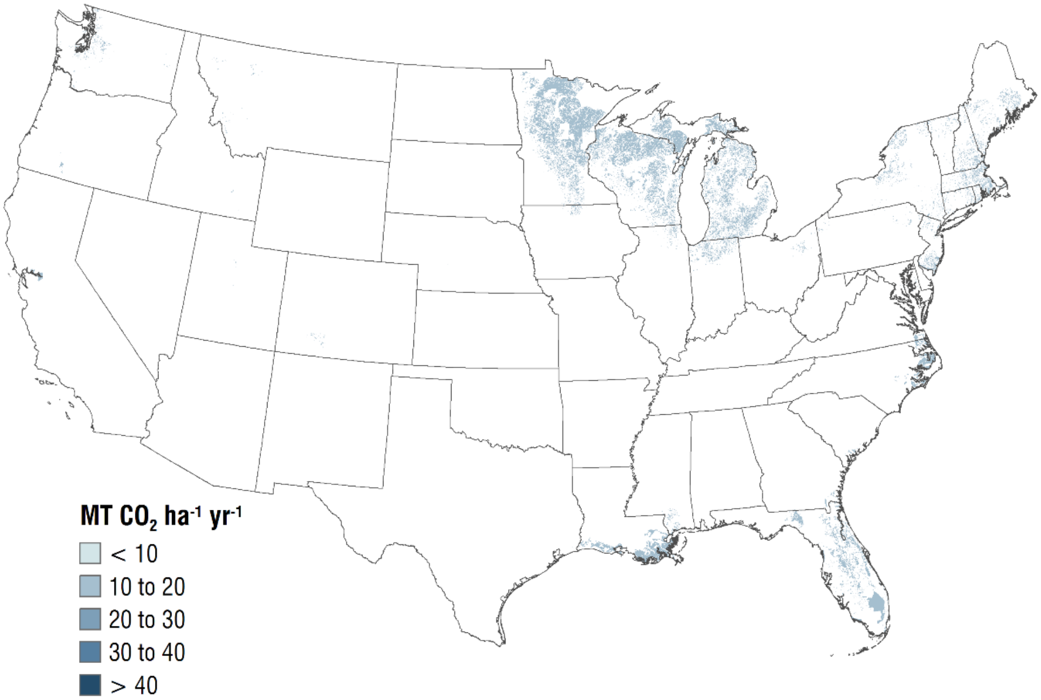
[50] Only national-scale emissions are estimated for 2016 to 2020 in the current Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-8: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

Figure 6-9: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*



Note: Only national-scale soil organic carbon stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for *Grassland Remaining Grassland*, including (1) aboveground and belowground biomass, dead wood and litter C for woodlands, as well as (2) soil organic C stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

The methodology is consistent with IPCC (2006). Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6.1 Representation of the U.S. Land Base), but include woody vegetation with C storage in aboveground and belowground biomass, dead wood and litter C (IPCC 2006) as described in the *Forest Land Remaining Forest Land* section. Carbon stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in *Grassland Land Remaining Grassland* are consistent with those in the *Forest Land Remaining Forest Land* section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2020) were used in the current Inventory. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland. The same methods are applied from 1990 to 2020 in order to ensure time-series consistency.

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic C stocks for *Grassland Remaining Grassland*, including: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil organic C stock changes are estimated for *Grassland Remaining Grassland* on non-federal lands according to land use histories recorded in the 2015 USDA NRI survey (USDA-NRCS 2018). Land-use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2015). NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2015 if the land use had been grassland for 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Grassland Remaining Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), the additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments, and federal land.[51]

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the activity data time series is updated.

Tier 3 Approach. Mineral soil organic C stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DayCent biogeochemical[52] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018).

The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 Manure Management and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) is an input to the DayCent model to estimate the influence of PRP manure on C stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence

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[51] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[52] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

intervals are estimated for each year between 1990 and 2015 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland.* Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Future Inventories will be updated with new activity data, and the time series will be recalculated for 2016 to 2020 (see the Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils, with the exception of the manure N deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the Inventory for federal grasslands. First, the PRP N manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2018) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic C stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

*Additional Mineral C Stock Change Calculation*s

A Tier 2 method is used to adjust annual C stock change estimates for mineral soils between 1990 and 2020 to account for additional C stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids N applied to agricultural land are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in *Grassland Remaining Grassland*. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic C storage rate is estimated at 0.38 metric tons C per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the *Cropland Remaining Cropland* section for organic soils and Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series (i.e., 2016 to 2020) are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Grassland Remaining Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-38 for each subsource (i.e., soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Grassland Remaining Grassland* ranges from more than 3,256 percent below and above the 2020 stock change estimate of 4.5 MMT CO_2 Eq. The large relative uncertainty is mostly due to large uncertainty in the Tier 3 method and variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	0.2	0.2	0.2	-31%	31%

Belowground live biomass	0.1	0.1	0.1	-16%	16%
Dead wood	2.3	1.8	2.8	-22%	22%
Litter	(0.2)	(0.4)	+	-104%	104%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(2.3)	(148.4)	143.9	-6,479%	6,479%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.9)	(9.9)	8.1	-986%	986%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(0.2)	(0.3)	(0.1)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.4	1.2	9.6	-77%	77%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**4.5**	**(142.0)**	**150.9**	**-3,256%**	**3,256%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. Changes in biomass and dead organic matter C stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are certainly significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Recalculations are associated with updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method, in addition to a correction in the estimation of biomass C. The correction is associated with foliage estimates for woodlands that had been based on values for non-woodland foliage in the previous Inventory. As a result of these new data, *Grassland Remaining Grassland* has a smaller loss of C compared to the previous Inventory, estimated at a reduction in C loss of 1.3 MMT CO_2 Eq., or 32 percent decrease in C loss, on average over the time series for *Grassland Remaining Grassland* compared to the previous Inventory.

Planned Improvements

Grasslands in Alaska are not currently included in the Inventory. This is a significant planned improvement and estimates are expected to be available in a future Inventory contingent on funding availability. Table 6-39 provides information on the amount of managed area in Alaska that is *Grassland Remaining Grassland*, which includes about 50 million hectares per year. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

Table 6-39: Area of Managed Land in *Grassland Remaining Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	327,446	277,406	50,040
1991	326,959	276,918	50,040
1992	326,462	276,422	50,040
1993	324,524	274,484	50,040
1994	322,853	272,813	50,040
1995	322,015	271,975	50,040
1996	321,164	271,123	50,040
1997	320,299	270,259	50,040
1998	318,214	268,174	50,040
1999	317,341	267,301	50,040
2000	316,242	266,202	50,040
2001	315,689	265,649	50,040
2002	315,232	265,192	50,040
2003	315,442	265,403	50,039
2004	315,459	265,421	50,038
2005	315,161	265,123	50,038
2006	314,841	264,804	50,037
2007	314,786	264,749	50,036
2008	314,915	264,878	50,037
2009	315,137	265,099	50,037
2010	314,976	264,942	50,035
2011	314,662	264,627	50,035
2012	314,466	264,413	50,053
2013	315,301	265,239	50,062
2014	316,242	266,180	50,062
2015	316,287	266,234	50,053
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Non-CO_2 Emissions from Grassland Fires (CRF Source Category 4C1)

Fires are common in grasslands, and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes, but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grassland of the United States (Including burning emissions in *Grassland Remaining Grassland* and *Land Converted to Grassland*) is a relatively small source of emissions, but it has increased by nearly 300 percent since 1990. In 2020, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2020 have averaged approximately 0.3 MMT CO_2 Eq. (12 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-40 and Table 6-41).

Table 6-40: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990		2005		2016	2017	2018	2019	2020
CH_4	0.1		0.3		0.3	0.3	0.3	0.3	0.3
N_2O	0.1		0.3		0.3	0.3	0.3	0.3	0.3
Total Net Flux	**0.2**		**0.7**		**0.6**	**0.6**	**0.6**	**0.6**	**0.6**

Table 6-41: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990		2005		2016	2017	2018	2019	2020
CH_4	3		13		11	12	12	12	12
N_2O	+		1		1	1	1	1	1
CO	84		358		324	345	331	341	334
NO_x	5		21		19	21	20	20	20

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this Inventory, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2014 (IPCC 2006). A data splicing method is used to estimate the emissions from 2015 to 2020, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2015). NRI has survey locations across the entire United States, but does not classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1 Representation of the U.S. Land Base).

The area of biomass burning in grasslands (*Grassland Remaining Grassland* and *Land Converted to Grassland*) is determined using 30-m fire data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2014.[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-42).

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[53] A planned improvement is underway to incorporate woodland tree biomass into the Inventory.

[54] See http://www.mtbs.gov.

Table 6-42: Thousands of Grassland Hectares Burned Annually

Year	Thousand Hectares
1990	317
2005	1,343
2016	NE
2017	NE
2018	NE
2019	NE
2020	NE

Notes: Burned area was not estimated (NE) for 2015 to 2020 but will be updated in a future Inventory. Burned area for the year 2014 is estimated to be 1,659 thousand hectares.

For 1990 to 2014, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this Inventory, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g N_2O per kg dry matter), CO (65 g CO per kg dry matter) and NO_x (3.9 g NO_x per kg dry matter) (IPCC 2006). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[55]

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2015 to 2020 because new activity data have not been compiled for these years. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2014, and the trend is used to approximate the 2015 to 2020 emissions. The Tier 1 method described previously will be applied to recalculate the 2015 to 2020 emissions in a future Inventory.

The same methods are applied from 1990 to 2014, and a data splicing method is used to extend the time series from 2015 to 2020 ensuring a consistent time series of emissions data. The trend extrapolation is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006).

Uncertainty

Emissions are estimated using a linear regression model with ARMA errors for 2015 to 2020. The linear regression ARMA model produced estimates of the upper and lower bounds of the emission estimate and the results are summarized in Table 6-43. Methane emissions from Biomass Burning in Grassland for 2020 are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 145 percent above the 2020 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq., or approximately 100 percent below and 145 percent above the 2020 emission estimate of 0.3 MMT CO_2 Eq.

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[55] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

Table 6-43: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.7	-100%	145%
Grassland Burning	N_2O	0.3	+	0.8	-100%	145%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grassland of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the Inventory. There is also uncertainty due to lack of reporting combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Quality control identified problems with input data for common reporting format tables in the spreadsheets, which have been corrected.

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A data splicing method is applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for the next Inventory will be to update the time series with new activity data from the Monitoring Trends in Burn Severity program and recalculate the emissions. Two other planned improvements have been identified for this source category, including a) incorporation of country-specific grassland biomass factors, and b) extending the analysis to include Alaska. In the current Inventory, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Both improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRF Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018).[56] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include *Land Converted to Grassland* in Alaska. Consequently, there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Table 6-47 in Planned Improvements) and the grassland area included in the inventory analysis.

Land use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for *Land Converted to Grassland*, but there is limited reporting of other pools in this Inventory. Losses of aboveground and belowground biomass, dead wood and litter C from *Forest Land Converted to Grassland* are reported, but these C stock changes are not estimated for other land use conversions to grassland.[57]

The largest C losses with *Land Converted to Grassland* are associated with aboveground biomass, belowground biomass, and litter C losses from *Forest Land Converted to Grassland* (see Table 6-44 and Table 6-45). These three pools led to net emissions in 2020 of 11.6, 2.1, and 4.6 MMT CO_2 Eq. (3.2, 0.6, and 1.3 MMT C), respectively. Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil organic C stocks, estimated at 43.9 MMT CO_2 Eq. (12.0 MMT C) in 2020. The gains are primarily associated with conversion of Other Land, which have relatively low soil organic C stocks, to Grassland that tend to have conditions suitable for storing larger amounts of C in soils, and also due to conversion of Cropland to Grassland that leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.8 MMT CO_2 Eq. (0.5 MMT C). The total net C stock change in 2020 for *Land Converted to Grassland* is estimated as a gain of 24.1 MMT CO_2 Eq. (6.6 MMT C), which represents an increase in C stock change of 584 percent compared to the initial reporting year of 1990.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Grassland	**(18.3)**	**(23.5)**	**(17.8)**	**(18.0)**	**(18.0)**	**(17.4)**	**(19.7)**
Mineral Soils	(18.9)	(25.0)	(19.1)	(19.4)	(19.3)	(18.7)	(21.0)

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[56] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[57] Changes in biomass C stocks are not currently reported for other conversions to grassland (other than forest land), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

Organic Soils	0.6	1.5	1.4	1.4	1.3	1.3	1.3
Forest Land Converted to Grassland	**19.4**	**19.4**	**18.1**	**18.1**	**18.1**	**18.1**	**18.1**
Aboveground Live Biomass	12.8	12.6	11.6	11.6	11.6	11.6	11.6
Belowground Live Biomass	2.3	2.2	2.1	2.1	2.1	2.1	2.1
Dead Wood	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	4.7	4.8	4.6	4.6	4.6	4.6	4.6
Mineral Soils	(0.1)	(0.1)	(0.1)	+	+	(0.1)	+
Organic Soils	+	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland	**(4.2)**	**(31.7)**	**(22.2)**	**(22.1)**	**(21.9)**	**(21.5)**	**(21.8)**
Mineral Soils	(4.2)	(31.7)	(22.3)	(22.2)	(21.9)	(21.6)	(21.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.2)**	**(1.4)**	**(0.9)**	**(1.0)**	**(0.9)**	**(0.9)**	**(1.0)**
Mineral Soils	(0.2)	(1.4)	(0.9)	(1.0)	(0.9)	(0.9)	(1.0)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**0.1**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.3	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**12.8**	**12.6**	**11.6**	**11.6**	**11.6**	**11.6**	**11.6**
Belowground Live Biomass	**2.3**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Dead Wood	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Litter	**4.7**	**4.8**	**4.6**	**4.6**	**4.6**	**4.6**	**4.6**
Total Mineral Soil Flux	**(23.4)**	**(58.2)**	**(42.4)**	**(42.5)**	**(42.2)**	**(41.3)**	**(43.9)**
Total Organic Soil Flux	**0.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.8**	**1.8**
Total Net Flux	**(3.1)**	**(37.0)**	**(22.6)**	**(22.7)**	**(22.4)**	**(21.5)**	**(24.1)**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-45: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Grassland	**(5.0)**	**(6.4)**	**(4.8)**	**(4.9)**	**(4.9)**	**(4.7)**	**(5.4)**
Mineral Soils	(5.2)	(6.8)	(5.2)	(5.3)	(5.3)	(5.1)	(5.7)
Organic Soils	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Converted to Grassland	**5.3**	**5.3**	**4.9**	**4.9**	**4.9**	**4.9**	**4.9**
Aboveground Live Biomass	3.5	3.4	3.2	3.2	3.2	3.2	3.2
Belowground Live Biomass	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(1.1)**	**(8.6)**	**(6.1)**	**(6.0)**	**(6.0)**	**(5.9)**	**(5.9)**
Mineral Soils	(1.2)	(8.6)	(6.1)	(6.1)	(6.0)	(5.9)	(6.0)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**+**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.3)**
Mineral Soils	+	(0.4)	(0.3)	(0.3)	(0.3)	(0.2)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1

Aboveground Live Biomass	**3.5**	**3.4**	**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
Belowground Live Biomass	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Litter	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Total Mineral Soil Flux	**(6.4)**	**(15.9)**	**(11.6)**	**(11.6)**	**(11.5)**	**(11.3)**	**(12.0)**
Total Organic Soil Flux	**0.2**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Total Net Flux	**(0.9)**	**(10.1)**	**(6.2)**	**(6.2)**	**(6.1)**	**(5.9)**	**(6.6)**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Grassland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of *Forest Land Converted to Grassland*, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic C stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter C stock changes for *Forest Land Converted to Grassland*. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020). There are limited data on the herbaceous grassland C stocks following conversion so default biomass estimates (IPCC 2006) for grasslands are used to estimate C stock changes (Note: litter and dead wood C stocks are assumed to be zero following conversion because no reference C density estimates exist for grasslands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass C that is lost abruptly with *Forest Land Converted to Grasslands* is estimated based on the amount of C before conversion and the amount of C following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady is reached. It was determined that using an IPCC Tier I approach that assumes all C is lost in the year of conversion for *Forest Land Converted to Grasslands* in the West and Great Plains states does not accurately characterize the transfer of C in woody biomass during abrupt or gradual land use change. To estimate this transfer of C in woody biomass, state-specific C densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of C stock changes from *Forest Land Converted to Grasslands* in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass C density was lost during conversion from Forest Land to Grasslands. This estimate was used to develop state-specific C density estimates for biomass, dead wood, and litter for Grasslands in the West and Great Plains states and these state-specific C densities were applied in the compilation system to estimate the C losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are characterized as woodlands are included in this category using FIA plot re-measurements and the methods and models described hereafter.

If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter that are not attached to live or standing dead trees at transect intersection. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). The same methods are applied from 1990 to 2020 in order to ensure time-series consistency. See Annex 3.13 for more information about reference C density estimates for forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for *Land Converted to Grassland* according to land use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2015 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes in mineral soils for most of the area in *Land Converted to Grassland*. C stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the times series of activity data is updated.

Tier 3 Approach*.* Mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical[58] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent

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[58] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland.* Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Future Inventories will be updated with new activity data, and the time series will be recalculated for 2016 to 2020 (see the Planned Improvements section in *Cropland Remaining Cropland*)

Tier 2 Approach*.* For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Grassland Remaining Grassland* and Annex 3.12. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section. Further elaboration on the methodology is also provided in Annex 3.12 for organic soils.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with a surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-46 for each subsource (i.e., biomass C stocks, mineral and organic C stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC

(2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Grassland* ranges from 153 percent below to 153 percent above the 2020 stock change estimate of 24.1 MMT CO_2 Eq. The large relative uncertainty around the 2020 stock change estimate is partly due to large uncertainties in biomass and dead organic matter C losses with *Forest Land Conversion to Grassland*. The large relative uncertainty is also partly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with the splicing method.

Table 6-46: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Grassland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(19.7)**	**(50.3)**	**10.9**	**-155%**	**155%**
Mineral Soil C Stocks: Tier 3	(17.3)	(47.7)	13.2	-176%	176%
Mineral Soil C Stocks: Tier 2	(3.8)	(7.0)	(0.6)	-85%	85%
Organic Soil C Stocks: Tier 2	1.3	+	2.7	-103%	103%
Forest Land Converted to Grassland	**18.1**	**4.9**	**31.3**	**-73%**	**73%**
Aboveground Live Biomass	11.6	(0.5)	23.7	-104%	104%
Belowground Live Biomass	2.1	(0.1)	4.2	-103%	104%
Dead Wood	(0.3)	(0.1)	+	-78%	100%
Litter	4.6	(0.2)	9.4	-104%	104%
Mineral Soil C Stocks: Tier 2	+	(0.2)	0.1	-348%	348%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-114%	114%
Other Lands Converted to Grassland	**(21.8)**	**(37.3)**	**(6.3)**	**-71%**	**71%**
Mineral Soil C Stocks: Tier 2	(21.9)	(37.4)	(6.3)	-71%	71%
Organic Soil C Stocks: Tier 2	0.1	+	0.2	-155%	155%
Settlements Converted to Grassland	**(1.0)**	**(1.7)**	**(0.2)**	**-76%**	**76%**
Mineral Soil C Stocks: Tier 2	(1.0)	(1.7)	(0.2)	-75%	75%
Organic Soil C Stocks: Tier 2	+	+	+	-292%	292%
Wetlands Converted to Grasslands	**0.2**	**+**	**0.5**	**-116%**	**116%**
Mineral Soil C Stocks: Tier 2	+	(0.1)	0.1	-882%	882%
Organic Soil C Stocks: Tier 2	0.2	+	0.5	-116%	116%
Total: Land Converted to Grassland	**(24.1)**	**(60.9)**	**12.7**	**-153%**	**153%**
Aboveground Live Biomass	**11.6**	**(0.5)**	**23.7**	**-104%**	**104%**
Belowground Live Biomass	**2.1**	**(0.1)**	**4.2**	**-103%**	**104%**
Dead Wood	**(0.3)**	**(0.1)**	**+**	**-78%**	**100%**
Litter	**4.6**	**(0.2)**	**9.4**	**-104%**	**104%**
Mineral Soil C Stocks: Tier 3	**(17.3)**	**(47.7)**	**13.2**	**-176%**	**176%**
Mineral Soil C Stocks: Tier 2	**(26.6)**	**(42.5)**	**(10.8)**	**-60%**	**60%**
Organic Soil C Stocks: Tier 2	**1.8**	**0.4**	**3.2**	**-77%**	**77%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. However, there are currently no datasets to evaluate the trends. Changes in biomass and dead organic matter C stocks are assumed to be negligible with the exception of forest lands, which are included in this analysis in other grasslands. This assumption will be further explored in a future Inventory.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland* for information on QA/QC steps.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in *Forest Land Converted to Grassland,* and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. As a result, *Land Converted to Grassland* has an estimated smaller gain in C of 2.93 MMT CO_2 Eq. on average over the time series. This represents a 15 percent decrease in C stock changes for *Land Converted to Grassland* compared to the previous Inventory.

Planned Improvements

The amount of biomass C that is lost abruptly or the slower changes that continue to occur over a decade or longer with *Forest Land Converted to Grasslands* will be further refined in a future Inventory. The current values are estimated based on the amount of C before conversion and an estimated level of C left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of C left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter C pools. In addition, biomass C stock changes will be estimated for *Cropland Converted to Grassland*, and other land use conversions to grassland, to the extent that data are available.

An additional planned improvement for the *Land Converted to Grassland* category is to develop an inventory of C stock changes for grasslands in Alaska. Table 6-47 provides information on the amount of managed area in Alaska that is *Land Converted to Grassland*, which is as high as 54 thousand hectares in 2011.[59] Note that areas of *Land Converted to Grassland* in Alaska for 1990 to 2001 are classified as *Grassland Remaining Grassland* because land use change data are not available until 2002. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

Table 6-47: Area of Managed Land in *Land Converted to Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	**Inventory**	**Not Included in Inventory**
1990	9,394	9,394	0
1991	9,485	9,485	0
1992	9,691	9,691	0
1993	11,566	11,566	0
1994	13,378	13,378	0
1995	13,994	13,994	0
1996	14,622	14,622	0
1997	15,162	15,162	0
1998	19,052	19,052	0
1999	19,931	19,931	0
2000	20,859	20,859	0
2001	21,968	21,968	0
2002	22,395	22,392	3

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[59] All of the *Land Converted to Grassland* according to the land representation is included in the inventory from 1990 through 2001 for the conterminous United States. However, there are no data to evaluate land use change in Alaska for this time period, and so the balance of the managed area that may be converted to grassland in these years is included in Grassland Remaining Grassland section. This gap in land use change data for Alaska will be addressed in a future Inventory.

2003	22,015	22,008	7
2004	22,557	22,547	10
2005	22,460	22,447	13
2006	22,718	22,702	16
2007	22,450	22,428	21
2008	22,685	22,661	24
2009	22,608	22,581	26
2010	22,664	22,634	29
2011	22,805	22,750	54
2012	22,643	22,596	47
2013	21,472	21,439	33
2014	20,195	20,163	33
2015	20,242	20,210	33
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.8 Wetlands Remaining Wetlands (CRF Category 4D1)

Wetlands Remaining Wetlands includes all wetland in an Inventory year that had been classified as wetland for the previous 20 years, and in this Inventory the flux estimates include Peatlands, Coastal Wetlands, and Flooded Land.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under Peatlands Remaining Peatlands), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for Peatlands Remaining Peatlands consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided for rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current Inventory estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., Peatlands Remaining Peatlands) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: *Sphagnum* bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from *Sphagnum* bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from Peatlands Remaining Peatlands using the Tier 1 approach. Current methodologies estimate only on-site N_2O and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines.

On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from Peatlands Remaining Peatlands were estimated to be 0.7 MMT CO_2 Eq. in 2020 (see Table 6-48 and Table 6-49) comprising 0.7 MMT CO_2 Eq. (708 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.15 kt) of CH_4 and 0.0006 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2020 were 6.2 percent less than total emissions in 2019.

Total emissions from Peatlands Remaining Peatlands have fluctuated between 0.7 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2020. Carbon dioxide emissions from Peatlands Remaining Peatlands have fluctuated between 0.7 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series. Nitrous oxide emissions showed a decreasing trend from 1990 until 1995, followed by an increasing trend through 2001. Nitrous oxide emissions decreased between 2001 and 2006, followed by a leveling off between 2008 and 2010, and a general decline between 2011 and 2020. Methane emissions decreased from 1990 until 1995, followed by an increasing trend through 2000, a period of fluctuation through 2010, and a general decline between 2010 and 2020 (emissions rose slightly from 2016 to 2017 but resumed the downward trend since).

Table 6-48: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	**1.1**	**1.1**	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**
Off-site	1.0	1.0	0.7	0.8	0.7	0.7	0.7
On-site	0.1	0.1	+	0.1	0.1	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Table 6-49: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	**1,055**	**1,101**	**733**	**829**	**792**	**755**	**708**
Off-site	985	1,030	686	774	741	706	662
On-site	70	71	47	55	51	49	46
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from Peatlands Remaining Peatlands were calculated by apportioning the annual weight of peat produced in the United States (Table 6-50) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1995 through 2017; USGS 2021a; USGS 2021b). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the

Alaska's Mineral Industry report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-51). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[60] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015); and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2019 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic C were estimated by multiplying the area of peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over time the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; in 2018, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports (USGS 2021a). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

Table 6-50: Peat Production of Lower 48 States (kt)

Type of Deposit	1990		2005		2016	2017	2018	2019	2020
Nutrient-Rich	595.1		657.6		388.1	423.3	415.0	410.4	417.1
Nutrient-Poor	55.4		27.4		52.9	74.7	62.0	45.6	12.9
Total Production	**692.0**		**685.0**		**441.0**	**498.0**	**477.0**	**456.0**	**430.0**

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2021) *Mineral Commodity Summaries: Peat (2021).*

Table 6-51: Peat Production of Alaska (Thousand Cubic Meters)

	1990		2005		2016	2017	2018	2019	2020
Total Production	49.7		47.8		93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014)*.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of

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[60] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] *Sphagnum* moss are extensive" (USGS 2008).

land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[61] The area of land managed for peat extraction in the lower 48 states of the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-52. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from Peatlands Remaining Peatlands in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-53. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-52: Peat Production Area of Lower 48 States (Hectares)

	1990[a]	2005	2016	2017	2018	2019	2020
Nutrient-Rich	5,951	6,576	3,881	4,233	4,150	4,104	4,171
Nutrient-Poor	554	274	529	747	620	456	129
Total Production	**6,920**	**6,850**	**4,410**	**4,980**	**4,770**	**4,560**	**4,300**

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.

Notes: Calculated using peat production values in Table 6-50, an assumed yield of 100 metric tons per hectare per year.

Table 6-53: Peat Production Area of Alaska (Hectares)

	1990	2005	2016	2017	2018	2019	2020
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	201	333	212	212	212
Total Production	**286**	**104**	**201**	**333**	**212**	**212**	**212**

Sources: Calculated using peat production values in Table 6-51, an assumed yield of 100 metric tons per hectare per year.

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emission estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O emissions, the area of nutrient-rich Peatlands Remaining Peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013).

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[61] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the area of Peatlands Remaining Peatlands was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-54 for the calculated area of ditches and drained land.

Table 6-54: Peat Production (Hectares)

	1990		2005		2016	2017	2018	2019	2020
Lower 48 States									
Area of Drained Land	6,574		6,508		4,190	4,731	4,532	4,332	4,085
Area of Ditches	346		343		221	249	239	228	215
Total Production	**6,920**		**6,850**		**4,410**	**4,980**	**4,770**	**4,560**	**4,300**
Alaska									
Area of Drained Land	272		99		191	317	202	202	202
Area of Ditches	14		5		10	17	11	11	11
Total Production	**286**		**104**		**201**	**333**	**212**	**212**	**212**

Sources: Calculated using peat production values in Tables Table 6-50 and Table 6-51, an assumed yield of 100 metric tons per hectare per year, and an assumed value of 5 percent ditch area.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. The same data sources were used throughout the time series, when available. When data were unavailable or the available data were outliers, missing values were estimates based on the past available data.

Uncertainty

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from Peatlands Remaining Peatlands for 2020, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.

- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-55. Carbon dioxide emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.6 and 0.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 17 percent below to 17 percent above the 2020 emission estimate of 0.71 MMT CO_2 Eq. Methane emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.002 and 0.007 MMT CO_2 Eq. This indicates a range of 58 percent below to 77 percent above the 2020 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.0003 and 0.0009 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 53 percent below to 53 percent above the 2020 emission estimate of 0.0006 MMT CO_2 Eq.

Table 6-55: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.7	0.6	0.8	-17%	17%
Peatlands Remaining Peatlands	CH_4	+	+	+	-58%	77%
Peatlands Remaining Peatlands	N_2O	+	+	+	-53%	53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The lower 48 states peat production estimates for Peatlands Remaining Peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2021*. The 2021 edition updated 2018 and 2019 peat production data and provided peat type production estimates for 2020. The updated data lowered previously estimated emissions for 2018 and 2019 by 0.4 percent and 2.9 percent versus estimated emissions for 2018 and 2019 in the previous (i.e., 1990 through 2019) Inventory for Peatlands Remaining Peatlands.

Although Alaska peat production data for 2015 through 2020 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013, 2014, 2015, 2016, 2017, 2018, 2019, and 2020 values were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated Alaska data are available for the next Inventory cycle, this will result in a recalculation in the next (i.e., 1990 through 2021) Inventory report.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from Peatlands Remaining Peatlands, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

During the next Inventory cycle, efforts are planned to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued. In addition, edits to the trends and methodology sections are planned based on expert review comments.

The USGS has not published a *Minerals Yearbook* since the 2018 Advance Release. If more recent versions of the Minerals Yearbook are made available, these updated data will be included in the next inventory cycle. Correspondence with USGS indicated the Minerals Yearbook publications undergo a lengthy editing process and may delay the release of the publications (Brioche 2021).

The implied emission factors will be calculated and included in this chapter for future Inventories. Currently, the N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations, so estimating the implied emission factor per total land area is not appropriate and are not generated in the CRF tables. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification.

Coastal Wetlands Remaining Coastal Wetlands

This Inventory recognizes Wetlands as a "land-use that includes land covered or saturated for all or part of the year, in addition to areas of lakes, reservoirs, and rivers." Consistent with ecological definitions of wetlands,[62] the United States has historically included under the category of Wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation.

Guidance on quantifying greenhouse gas emissions and removals on Coastal Wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*)*,* which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon and the gain-loss method for biomass and DOM. Presently, this Inventory does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation.

The United States recognizes both Vegetated Wetlands and Unvegetated Open Water as Coastal Wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in Vegetated Coastal Wetlands and does not occur in Unvegetated Open Water Coastal Wetlands. The United States takes the additional step of recognizing that stock losses occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands.

This Inventory includes all privately-owned and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores on the conterminous United States, but does not include *Coastal Wetlands Remaining Coastal Wetlands* in Alaska or Hawaii. Seagrasses are not currently included within the Inventory due to insufficient data on distribution, change through time and carbon (C) stocks or C stock changes as a result of anthropogenic influence.

Under the *Coastal Wetlands Remaining Coastal Wetlands* category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*,
2) Carbon stock changes on *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*,

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[62] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2021.

3) Carbon stock changes on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*, and

4) *Nitrous Oxide Emissions from Aquaculture in Coastal Wetlands*.

Vegetated coastal wetlands hold C in all five C pools (i.e., aboveground, belowground, dead organic matter [DOM; dead wood and litter], and soil) though typically soil C and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). Vegetated Coastal Wetlands are net accumulators of C over centuries to millennia as soils accumulate C under anaerobic soil conditions and in plant biomass. Large emissions from soil C and biomass stocks occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands (e.g., when Vegetated Coastal Wetlands are lost due to subsidence, channel cutting through Vegetated Coastal Wetlands), but are still recognized as Coastal Wetlands in this Inventory. These C stock losses resulting from conversion to Unvegetated Open Water Coastal Wetlands can cause the release of decades to centuries of accumulated soil C, as well as the standing stock of biomass C. Conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands, either through restoration efforts or naturally, initiates the building of C stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for CH_4 emissions, coastal wetlands in salinity conditions greater than 18 parts per thousand have little to no CH_4 emissions compared to those experiencing lower salinity brackish and freshwater conditions. Conversion of Vegetated Coastal Wetlands to or from Unvegetated Open Water Coastal Wetlands are conservatively assumed to not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the N derived from consumption of the applied food stock that is then excreted as N load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic N loading from the watershed and atmospheric deposition, these emissions are not reported here to avoid double-counting of indirect N_2O emissions with the Agricultural Soils Management, Forest Land and Settlements categories.

The *Wetlands Supplement* provides methodologies for estimating C stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, C stock changes from mangroves may be reported under the Forest Land category or under Coastal Wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the Forest Land category. Mangrove forests that are less than 5 m are reported under Coastal Wetlands. All other non-drained, intact coastal marshes are intended to be reported under Coastal Wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such estimates of C stock changes, emissions of CH_4, and emissions of N_2O from aquaculture are included in this Inventory. At the present stage of inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[63] with NRI, FIA and NLDC data used to compile the Land Representation. However, a check was undertaken to confirm that Coastal Wetlands recognized by C-CAP represented a subset of Wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-56. *Coastal Wetlands Remaining Coastal Wetlands* are generally a net C sink, with the fluxes ranging from -3.7 to -4.8 MMT CO_2 Eq. across the majority of the time series, however, between 2006 and 2010 they were a net source of emissions (ranging from of 5.2 to 5.5 MMT CO_2 Eq.), resulting from large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-56). Recognizing removals of CO_2 to soil of 10.2 MMT CO_2 Eq. and CH_4 emissions of 3.8 MMT CO_2 Eq. in 2020, *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are a net sink of 6.4 MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as Veg*etated Coastal Wetlands Converted to Unvegetated Coastal* Wetlands, drive an emission of 1.5 MMT CO_2 Eq. over the past five years, primarily from

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[63] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed August 2021.

soils. Building of new wetlands from open water, recognized as *Unvegetated Coastal Wetlands Converted to Vegetated Coastal*, results each year in removal of 0.03 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.1 to 0.2 MMT CO_2 Eq. In all, *Coastal Wetlands* are a net sink of 4.8 MMT CO_2 Eq. in 2020.

Table 6-56: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(6.5)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**
Biomass C Flux	(+)	0.1	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Net CH_4 Flux	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Total Biomass C Flux	**+**	**0.1**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(8.5)**	**(7.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**
Total CH_4 Flux	**3.7**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Total Flux	**(4.6)**	**(3.7)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* comprised of tidally influenced palustrine emergent marsh (660,448 ha), palustrine scrub shrub (133,148 ha) and estuarine emergent marsh (1,894,045 ha), estuarine scrub shrub (94,110 ha) and estuarine forested wetlands (195,619 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in subtropical states along the Gulf of Mexico, do not attain the height status to be recognized as Forest Land, and are therefore always classified within Vegetated Coastal Wetlands. *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are found in cold temperate (53,973 ha), warm temperate (896,253 ha), subtropical (1,964,383 ha) and Mediterranean (62,762 ha) climate zones.

Soils are the largest C pool in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of both autochthonous and allochthonous decaying organic matter. Soil C emissions are not assumed to occur in coastal wetlands that remain vegetated. This Inventory includes changes in biomass C stocks along with soils. Methane emissions from decomposition of organic matter in anaerobic conditions are present at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of C stock changes or CH_4 emissions.

Table 6-57 through Table 6-59 below summarize nationally aggregated biomass and soil C stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Intact *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* hold a total biomass C stock of 88.8 MMT C. Removals from biomass C stocks in 2020 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-57 and Table 6-58). Carbon dioxide emissions from biomass in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* between 2002 and 2011 are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large C stock within the top 1 meter of soil (estimated to be 804 MMT C) to which C accumulated at a rate of 10.2 MMT CO_2 Eq. (2.8 MMT C) in 2020, a value that has remained relatively constant across the reporting period. For *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, methane emissions of 3.8 of MMT CO_2 Eq. (154 kt CH_4) in 2020 (Table 6-59) offset C removals resulting in a net removal of 6.4 MMT CO_2 Eq. in 2020; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of Vegetated Coastal Wetlands through human activities slowed considerably in the 1970s and the current annual rates of C stock change and CH_4 emissions are relatively constant over time.

Table 6-57: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	(+)	0.1	(+)	(+)	(+)	(+)	(+)
Soil Flux	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Total C Stock Change	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-58: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Total C Stock Change	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**

+ Absolute value does not exceed 0.05 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-59: CH_4 Emissions from *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2016	2017	2018	2019	2020
Methane Emissions (MMT CO_2 Eq.)	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Methane Emissions (kt CH_4)	149	151	153	153	153	153	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass C stocks, soil C stocks and emissions of CH_4 for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Dead organic matter is not calculated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since it is assumed to be in steady state (IPCC 2014).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Above- and below ground biomass C Stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-60). Biomass is not sensitive to soil organic content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017). Root to shoot ratios from the *Wetlands Supplement* (Table 6-62; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass C stock changes per year for *Wetlands Remaining Wetlands* were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-60: Area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*, and *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (ha)

Year	1990	2005	2016	2017	2018	2019	2020
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,985,512	2,988,258	2,972,368	2,972,634	2,974,900	2,976,166	2,977,432
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	953	1,775	2,406	2,406	2,406	2,406	2,406

Table 6-61: Aboveground Biomass Carbon Stocks for *Vegetated Coastal Wetlands* (t C ha^{-1})

	Climate Zone			
Wetland Type	**Cold Temperate**	**Warm Temperate**	**Subtropical**	**Mediterranean**
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	3.05	3.10	17.83	3.44
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

Source: All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017).

Table 6-62: Root to Shoot Ratios for *Vegetated Coastal Wetlands*

	Climate Zone			
Wetland Type	**Cold Temperate**	**Warm Temperate**	**Subtropical**	**Mediterranean**
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63

Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	1.15	1.15	0.96	3.63
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

Source: All values from IPCC (2014).

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* for both mineral and organic soils. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-63; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Callaway et al. 2012a&b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016).

Tier 2 level estimates of soil C removals associated with annual soil C accumulation on managed *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* were developed with country-specific soil C removal factors multiplied by activity data of land area for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on an annual basis. To estimate soil C stock changes, no differentiation is made between organic and mineral soils since currently no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-63: Annual Soil Carbon Accumulation Rates for *Vegetated Coastal Wetlands* (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.01	1.54	0.45	0.85
Palustrine Emergent Wetland	1.01	1.54	0.45	0.85
Estuarine Forested Wetland	1.01	0.82	0.87	0.85
Estuarine Scrub/Shrub Wetland	1.01	0.82	1.09	0.85
Estuarine Emergent Wetland	2.17	0.82	1.09	0.85

Source: All data from Lu and Megonigal (2017)[64]

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and as a result CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty

Underlying uncertainties in the estimates of soil and biomass C stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil C stocks, biomass C stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing

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[64] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

data. Uncertainty specific to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* include differentiation of palustrine and estuarine community classes, which determines the soil C stock and CH_4 flux applied. Uncertainties for soil and biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-64 for each subsource (i.e., soil C, biomass C and CH_4 emissions). The combined uncertainty across all subsources is +/-36.6 percent, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 2020, the total flux was -6.4 MMT CO_2 Eq., with lower and upper estimates of -8.7 and -4.0 MMT CO_2 Eq.

Table 6-64: IPCC Approach 1 Quantitative Uncertainty Estimates for C Stock Changes and CH_4 Emissions occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(0.03)	-24.1%	24.1%
Soil C Stock Change	CO_2	(10.2)	(12.0)	(8.4)	-17.8%	17.8%
CH_4 emissions	CH_4	3.8	2.7	5.0	-29.8%	29.8%
Total Flux		**(6.4)**	**(8.7)**	**(4.0)**	**-36.6%**	**36.6%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil C stock datasets have been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads who reviewed summary tables against reviewed sources. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in this Inventory. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass C stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stock and biomass estimates for coastal wetlands.[65] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent updated changes in soil C stocks for estuarine emergent wetlands.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass C stocks into the *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands is a source of emissions from soil, biomass, and DOM C stocks. An estimated 1,488 ha of Vegetated Coastal Wetlands were converted to Unvegetated Open Water Coastal Wetlands in 2020, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquafer extraction. Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. Land Representation is recognized as falling under the Wetlands category within this Inventory. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This Inventory adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland C loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized C is immediately returned to the atmosphere (as assumed for terrestrial land use categories), rather than redeposited in long-term C storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland C based upon the geomorphic setting of the depositional environment.

In 2020, there were 1,488 ha of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT

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[65] See https://serc.si.edu/coastalcarbon; accessed August 2021.

CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, while DOM C stock loss was present it was minimal (Table 6-60, Table 6-65, and Table 6-66). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-60).

Table 6-65: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-66: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	+	+	+	+	+	+	+
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	0.5	0.7	0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Absolute value does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Biomass C stock changes for palustrine and estuarine marshes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass C stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass C stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[66]; Table 6-61). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a

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[66] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Conversion to open water results in emissions of all DOM C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM C stock.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. Country-specific soil C stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis demonstrated that it was not justified to stratify C stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil C stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil C loss with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands is assumed to affect soil C stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass C stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al.

2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (+/-10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Uncertainty estimates are presented in Table 6-67 for each subsource (i.e., soil C, biomass C, and DOM emissions). The combined uncertainty across all subsources is +/- 32.0 percent, which is driven by the uncertainty in the soil C estimates. In 2020, the total C flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-67: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	24.1%
Dead Organic Matter C Stock	0.0005	0.000	0.001	-25.8%	25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**32.0%**

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil C stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in the Inventory. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014) Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the United States. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil C returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the Inventory.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in Section 6.1 Representation of the U.S. Land Base, is recognized as Coastal Wetlands within this Inventory. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass, DOM and soil C accumulation on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* begins with vegetation establishment.

Within the United States, conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands* is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetlands restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2020, 2,406 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-59). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-68 and Table 6-69). The soil C stock has increased during the Inventory's reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM C stock increases are present they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2020), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of *Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-68: CO_2 Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2016	2017	2018	2019	2020
Biomass C Flux	(+)		(0.1)		(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)		(+)		0	0	0	0	0
Soil C Flux	(+)		(+)		(+)	(+)	(+)	(+)	(+)

Total C Stock Change	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-69: CO_2 Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

+ Absolute value does not exceed 0.005 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks, and CH_4 emissions for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass C stock changes for palustrine and estuarine marsh vegetation are presented for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets (Table 6-58). C-CAP provides peer reviewed country-level mapping of coastal wetland distribution, including conversion to and from open water. Biomass C stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-61; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[67]). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to Vegetated Coastal Wetlands results in the establishment of a standing biomass C stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands

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[67] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years. Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass C stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil C stock changes are estimated for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*. Country-specific soil C removal factors associated with soil C accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). Soil C stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil C stock change no differentiation is made for soil type (i.e., mineral, organic). Soil C removal factors were developed from literature references that provided soil C removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-63 for values).

Tier 2 level estimates of C stock changes associated with annual soil C accumulation in Vegetated Coastal Wetlands were developed using country-specific soil C removal factors multiplied by activity data on Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass C stock changes include uncertainties associated with country-specific (Tier 2) literature values of these C stocks and assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al.

2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-62), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-70 for each subsource (i.e., soil C, biomass C and DOM emissions). The combined uncertainty across all subsources is +/-33.4 percent. In 2020, the total C flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.07 MMT CO_2 Eq.

Table 6-70: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes Occurring within *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range (MMT CO_2 Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.12)	(0.08)	-20.0%	20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	25.8%
Soil C Stock Flux	(0.007)	(0.008)	(0.005)	-17.8%	17.8%
Total Flux	**(0.1)**	**(0.14)**	**(0.07)**	**-33.4%**	**33.4%**

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass C reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the Coastal Wetland Inventory team leads before inclusion in the inventory. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of published data quantifying soil C stock and biomass in coastal wetlands. Reference values for soil and biomass C stocks will be updated as new data emerge. Refined error analysis combining land cover change, soil and biomass C stock estimates will be updated at those times.

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the inventory.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N_2O emissions increasing from 0.1 in 1990 to upwards of 0.2 MMT CO_2 Eq. between 1992 and 2010, and reducing again to 0.1 MMT CO_2 Eq. between 2015 and 2020 (Table 6-71). Aquaculture production data were updated through 2018; data through 2020 are not yet available and in this analysis are held constant with 2018 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-71: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990	2005	2016	2017	2018	2019	2020
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Emissions (kt N_2O)	0.4	0.6	0.5	0.5	0.5	0.5	0.5

Methodology and Time-Series Consistency

The methodology to estimate N_2O emissions from Aquaculture in Coastal Wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2021), from which activity data for this analysis is derived.[68] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions from aquaculture is not sensitive to salinity using IPCC approaches and as such the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N_2O emissions.

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[68] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2019-report; accessed August 2021.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-72 for N_2O emissions. The combined uncertainty is +/-116 percent. In 2020, the total flux was 0.16 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.34 MMT CO_2 Eq.

Table 6-72: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.16	0.00	0.34	-116%	116%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The Coastal Wetlands Inventory team consulted with the Coordinating Lead Authors of the Coastal Wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

A NOAA report was released in 2021 that contains updated fisheries data through 2018 and the 2017 production estimate was revised from 283,808 to 286,287 MT, although it did not affect the resulting emissions (National Marine Fisheries Service 2021). The updated production value was applied for 2017, and the 2018 value was applied in 2019 and 2020. This resulted in an increase of N_2O emissions by 0.02 MMT CO_2 Eq. (0.04 kt N_2O), a 7.7 percent increase, for 2018 and 2019 compared to the previous Inventory.

Flooded Land Remaining Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural emission of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation, but these waterbodies would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as "reservoirs" or "other constructed waterbodies" (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of "other constructed waterbodies" including freshwater ponds and canals/ditches.

Land that has been flooded for greater than 20 years is defined as Flooded Land Remaining Flooded Land and land flooded for 20 years or less is defined as Land Converted to Flooded Land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding as labile organic matter is rapidly degraded but declines to a steady background level approximately 20 years after flooding. Emissions of CH_4 are estimated for Flooded Land Remaining Flooded Land, but CO_2 emissions are not included as they are primarily the result of decomposition of organic matter entering the waterbody from the catchment or contained in inundated soils are included elsewhere in the IPCC guidelines (IPCC 2006).

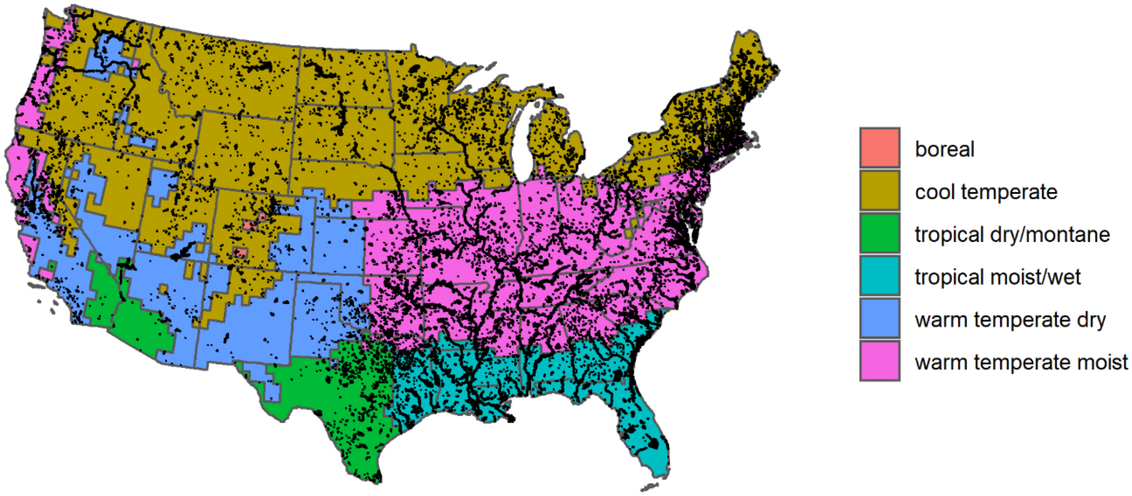
Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting of N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Volume 4, Chapter 11, *2006 IPCC Guidelines*) and wastewater management (Volume 5, Chapter 6, *2006 IPCC Guidelines*).

Emissions from Flooded Land Remaining Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a "drawdown zone" or "inundation area." Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2020, the conterminous United States hosted 7.2 million hectares of reservoir and associated inundation areas in the Flooded Land Remaining Flooded Land category (see Methods below for calculation details). These reservoirs are distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-10) (IPCC 2019). Alaska, Hawaii, and U.S. Territories are not included in this report due to a lack of data (see Methodology).

Figure 6-10: U.S. reservoirs (black polygons) in the Flooded Land Remaining Flooded Land category in 2020. Colors represent climate zone used to derive IPCC default emission factors.



Methane is produced in reservoirs through the microbial breakdown of organic matter. Per unit area, CH_4 emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae), but negatively with system size (i.e., depth, surface area). Methane produced in reservoirs can be emitted from the surface of reservoirs and inundation areas or downstream of the flooded land as CH_4 enriched water passes through the dam and the downstream river.

Table 6-73 and Table 6-74 below summarize nationally aggregated CH_4 emissions from reservoirs and associated inundation areas. The increase in CH_4 emissions through the time series is attributable to reservoirs matriculating from the Land Converted to Flooded Land category into the Flooded Land Remaining Flooded Land category.

Table 6-73: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**16.0**	**17.4**	**17.5**	**17.5**	**17.5**	**17.5**	**17.5**
Surface Emission	14.7	16.0	16.1	16.1	16.1	16.1	16.1
Downstream Emission	1.3	1.4	1.4	1.4	1.4	1.4	1.4
Inundation Areas	**1.2**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Surface Emission	1.1	1.2	1.2	1.2	1.2	1.2	1.2
Downstream Emission	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**17.2**	**18.7**	**18.8**	**18.8**	**18.8**	**18.8**	**18.8**

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-74: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**640**	**696**	**700**	**700**	**700**	**700**	**700**
Surface Emission	587	639	642	642	642	642	642
Downstream Emission	53	57	58	58	58	58	58
Inundation Areas	**48**	**53**	**53**	**53**	**53**	**53**	**53**
Surface Emission	44	48	49	49	49	49	49
Downstream Emission	4	4	4	4	4	4	4
Total	**688**	**749**	**753**	**753**	**753**	**753**	**753**

Note: Alaska, Hawaii, and U.S. Territories not included.

Methane emissions from reservoirs and inundation areas are greatest in Texas (Figure 6-11, Table 6-75) due to 1) the large expanse of reservoirs and inundation areas in the state (Figure 6-10) and 2) the high CH_4 emission factor for the tropical dry/montane climate zone which encompasses a majority of the flooded land area in the state (Figure 6-10, Table 6-75). Florida has the second greatest CH_4 emission from reservoirs and inundation areas in the United States, but the emissions are less than half of that from Texas. Louisiana and Georgia have the third and fourth greatest CH_4 emission, respectively, in accordance with the relatively high extent of flooded lands in the states and the high emission factor for CH_4 in the tropical moist/wet biome.

Twenty five percent of the increase in CH_4 emissions from 1990 to 2005 for this subcategory is due to the transition of Lakes Sakakawea and Oahe in North Dakota and South Dakota to Flooded Land Remaining Flooded Land between 2000 and 2003 (i.e., they were emitting CH_4 prior to 2000 and the emissions were included in the Land Converted to Flooded Land category but these emissions are now included in Land Converted to Flooded Land). Combined, these two large reservoirs have a surface area in excess of 0.25 million hectares.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land (kt CH_4)

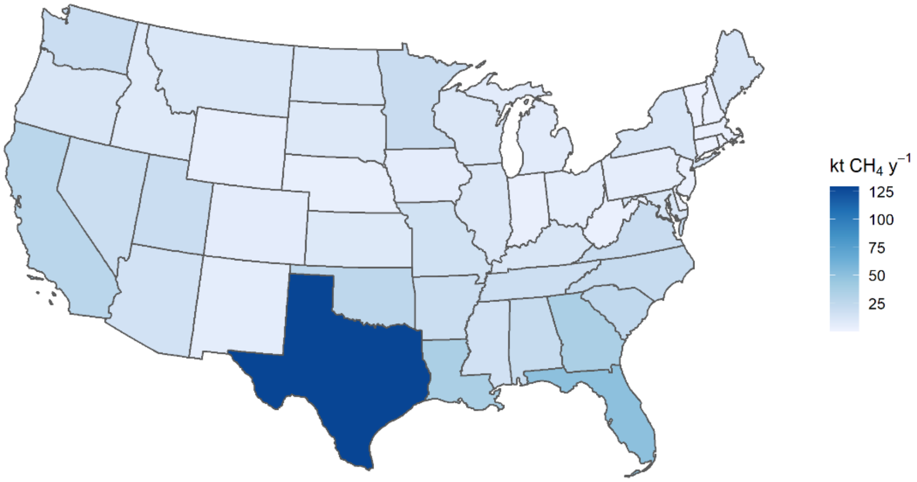


Table 6-75: Surface and Downstream CH_4 Emissions (kt CH_4) from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land in 2020

	Reservoir		Inundation area		Total	
State	Downstream	Ssurface	Downstream	Surface	Downstream	Surface
Alabama	2	19	+	+	2	19
Arizona	1	12	+	1	1	14
Arkansas	2	17	+	1	2	17
California	2	24	+	1	2	26
Colorado	+	5	+	+	+	6
Connecticut	+	2	+	+	+	2
Delaware	+	1	NO	NO	+	1
District of Columbia	+	+	NO	NO	+	+
Florida	4	47	NO	NO	4	47
Georgia	3	33	+	+	3	33
Idaho	1	8	+	+	1	8
Illinois	1	9	+	1	1	10
Indiana	+	3	+	1	+	3
Iowa	+	4	+	2	1	6
Kansas	1	6	+	3	1	9
Kentucky	1	10	+	1	1	11

Louisiana	3	33	+	1	3	33
Maine	1	11	NO	NO	1	11
Maryland	1	11	+	+	1	11
Massachusetts	+	3	+	+	+	3
Michigan	1	6	+	+	1	6
Minnesota	2	19	NO	NO	2	19
Mississippi	1	12	+	3	1	15
Missouri	1	13	+	2	1	14
Montana	1	10	+	+	1	10
Nebraska	+	3	+	+	+	3
Nevada	2	18	+	+	2	18
New Hampshire	+	3	+	+	+	3
New Jersey	+	3	NO	NO	+	3
New Mexico	+	3	+	2	+	5
New York	1	10	+	+	1	11
North Carolina	2	19	+	1	2	20
North Dakota	1	10	+	+	1	10
Ohio	+	4	+	1	+	5
Oklahoma	2	19	+	5	2	24
Oregon	1	11	NO	NO	1	11
Pennsylvania	+	4	+	+	+	5
Rhode Island	+	1	NO	NO	+	1
South Carolina	2	23	NO	NO	2	23
South Dakota	1	8	+	+	1	8
Tennessee	1	16	+	1	1	16
Texas	9	99	2	20	11	119
Utah	2	18	+	+	2	18
Vermont	+	2	+	+	+	2
Virginia	2	18	+	+	2	19
Washington	2	18	+	+	2	18
West Virginia	+	2	+	+	+	2
Wisconsin	1	10	NO	NO	1	10
Wyoming	+	4	+	+	+	4

+ Indicates values less than 0.5 kt

NO (Not Occurring)–Indicates no reservoir or inundation area in the state.

Note: Alaska and Hawaii not included.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land follow the Tier 1 methodology in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-76). Downstream emissions are calculated as 9 percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs and inundation areas are calculated as the sum of surface and downstream emissions. National emissions are calculated as the sum of state emissions.

The IPCC default surface emission factors used in the Tier 1 methodology are derived from model predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, table 7A.2) which were collapsed into 6 climate zones using a regression tree approach. All six aggregated climate zone are present in the conterminous United States.

Table 6-76: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land

Climate	Surface emission factor ($MT\ CH_4\ ha^{-1}\ y^{-1}$)
Boreal	0.0136
Cool Temperate	0.054
Warm Temperate Dry	0.1509
Warm Temperate Moist	0.0803
Tropical Dry/Montane	0.2837
Tropical Moist/Wet	0.1411

Area estimates

The Reservoirs in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[69] the National Lakes Assessment (NLA)[70] data, the National Inventory of Dams (NID),[71] and the Navigable Waterways (NW)[72] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies in these data sets that were greater than 20 years old, greater than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered reservoirs in Flooded Land Remaining Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the inventory of reservoirs.

The IPCC (2019) allows for the exclusion of reservoirs from the Inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the Inventory based on expert judgment that neither the surface area or water residence time was substantially altered by their associated dams. EPA assumes that all other waterbodies identified through the six criteria described above were substantially impacted by the construction of dams.

EPA assumes that all reservoirs included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore included in the inventory. Reservoir age was determined from the year the dam was completed as reported in the NID (available for 40,012 out of 54,670 reservoirs). When dam completion year was not available, the reservoir was assumed to be greater than 20 years old. Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[73]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the Inventory. Surface areas for reservoirs and associated inundation areas were taken from NHD or the NW and the final inventory of reservoirs and associated inundation areas was screened to ensure no waterbodies were duplicated.

Many reservoirs are surrounded by land that is dry for a portion of the year but is periodically flooded when water inflows to the reservoir exceed outflows and the reservoir surface area expands into surrounding lands. This can occur for a variety of reasons including high rates of water runoff from the watershed (i.e., snow melt, large precipitation events), deliberate efforts to raise water levels for seasonal recreation or wildlife habitat, and

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[69] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[70] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[71] See https://nid.sec.usace.army.mil.

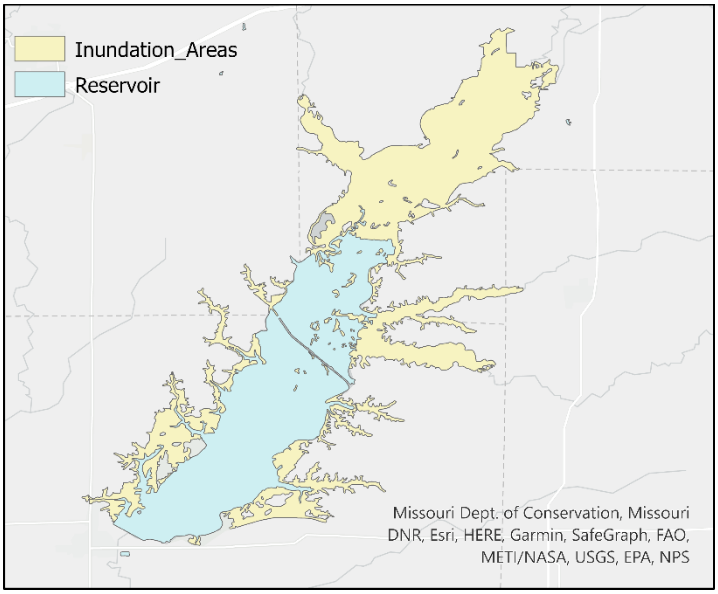
[72] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[73] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

management efforts to reduce inflows to downstream systems. These periodically flooded lands are represented as “Inundation Areas” in the NHDArea layer (Figure 6-12). Inundation areas are considered equivalent to “drawdown zones” in IPCC (2019) and CH_4 emissions from these lands are estimated using the same methodology as for reservoirs.

The surface area of reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land increased by approximately 10 percent from 1990 to 2020 (Table 6-77) due to reservoirs matriculating into Flooded Land Remaining Flooded Land when they reached 20 years of age.

Figure 6-12: Example of a Reservoir and Associated Inundation Area



Missouri Dept. of Conservation, Missouri DNR, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS

Table 6-77: National Totals of Reservoirs and Associated Inundation Area Surface Area (millions of ha) in Flooded Land Remaining Flooded Land

Surface Area (millions of ha)	1990	2005	2016	2017	2018	2019	2020
Reservoir	6.05	6.70	6.76	6.76	6.76	6.76	6.76
Inundation Area	0.39	0.43	0.44	0.44	0.44	0.44	0.44

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-78: State breakdown of Reservoirs and Associated Inundation Area Surface Area (millions of ha) in Flooded Land Remaining Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	0.17	0.21	0.21	0.21	0.21	0.21	0.21
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.17	0.20	0.20	0.20	0.20	0.20	0.20
California	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Colorado	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Connecticut	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Delaware	0.02	0.02	0.02	0.02	0.02	0.02	0.02
District of Columbia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Florida	0.32	0.33	0.33	0.33	0.33	0.33	0.33
Georgia	0.24	0.25	0.25	0.25	0.25	0.25	0.25
Idaho	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Illinois	0.11	0.12	0.13	0.13	0.13	0.13	0.13
Indiana	0.03	0.04	0.04	0.04	0.04	0.04	0.04

Iowa	0.06	0.08	0.08	0.08	0.08	0.08	0.08
Kansas	0.07	0.09	0.09	0.09	0.09	0.09	0.09
Kentucky	0.13	0.13	0.13	0.13	0.13	0.13	0.13
Louisiana	0.22	0.23	0.24	0.24	0.24	0.24	0.24
Maine	0.20	0.21	0.21	0.21	0.21	0.21	0.21
Maryland	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Massachusetts	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Michigan	0.11	0.12	0.12	0.12	0.12	0.12	0.12
Minnesota	0.33	0.34	0.34	0.35	0.35	0.35	0.35
Mississippi	0.14	0.15	0.15	0.15	0.15	0.15	0.15
Missouri	0.12	0.18	0.18	0.18	0.18	0.18	0.18
Montana	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Nebraska	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Nevada	0.10	0.10	0.10	0.10	0.10	0.10	0.10
New Hampshire	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New Jersey	0.03	0.03	0.03	0.03	0.03	0.03	0.03
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.18	0.18	0.18	0.18	0.18	0.18	0.18
North Carolina	0.23	0.25	0.25	0.25	0.25	0.25	0.25
North Dakota	0.03	0.19	0.19	0.19	0.19	0.19	0.19
Ohio	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Oklahoma	0.25	0.27	0.27	0.27	0.27	0.27	0.27
Oregon	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Pennsylvania	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Rhode Island	0.01	0.01	0.01	0.01	0.01	0.01	0.01
South Carolina	0.19	0.20	0.20	0.20	0.20	0.20	0.20
South Dakota	0.05	0.15	0.15	0.15	0.15	0.16	0.16
Tennessee	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Texas	0.57	0.62	0.62	0.62	0.62	0.62	0.62
Utah	0.13	0.14	0.17	0.17	0.17	0.17	0.17
Vermont	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Virginia	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Washington	0.19	0.19	0.19	0.19	0.19	0.19	0.19
West Virginia	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Wisconsin	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wyoming	0.07	0.07	0.08	0.08	0.08	0.08	0.08
Total	**6.44**	**7.13**	**7.20**	**7.20**	**7.20**	**7.20**	**7.20**

Note: Alaska, Hawaii, and U.S. Territories not included.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land (Table 6-79) are developed using the IPCC Approach 2 and include uncertainty in the default emission factors and land areas. Uncertainty ranges for the emission factors are provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of +/-15 percent for the reservoir and associated inundation area estimates is assumed and is based on expert judgment.

Table 6-79: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land

Source	**Gas**	**2020 Emission Estimate**	**Uncertainty Range Relative to Emission Estimate**[a]			
		(MMT CO_2 Eq.)	**(MMT CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**

Reservoir						
Surface	CH_4	16.1	15.7	16.4	-2%	2%
Downstream	CH_4	1.5	1.4	1.8	-6.9%	22.4%
Inundation Area						
Surface	CH_4	1.2	1.2	1.2	-2.3%	2.5%
Downstream	CH_4	0.1	0.1	0.1	-10.1%	17.5%
Total	**CH_4**	**18.8**	**18.5**	**19.3**	**-1.8%**	**2.6%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[74] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

The EPA is measuring greenhouse gas emissions from 108 flooded lands (reservoirs) in the conterminous United States. The survey is expected to be complete by September 2023 and the data will be used to predict greenhouse gas emission rates for all U.S. flooded lands. The Inventory will be updated at that time using these country-specific emission factors developed through the measurement campaign.

Hawaii, Alaska, and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[75] an enhanced version of the NHD used in this Inventory.

To verify that waterbodies contained in NW are subject to water level management, EPA will overlay the NW with other spatial datasets of water control structures including the inventory of U.S. Army Corps of Engineers locks for water navigation[76] and dams/weirs contained in the NHDPlus HighRes.

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[74] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[75] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

[76] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::locks/about.

Emissions from Flooded Land Remaining Flooded Land–Other Constructed Waterbodies

The IPCC (IPCC 2019) provides emission factors for several types of "other constructed waterbodies" including freshwater ponds and canals/ditches. IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." Furthermore, the IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) defines a size threshold of 8 ha to distinguish reservoirs from "other constructed waterbodies." For this Inventory, ponds are defined as managed flooded land that are 1) less than 8 ha in surface area, and 2) not categorized as canals/ditches. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emissions than the latter. Activity data on pond salinity are not uniformly available for the conterminous United States and all ponds in the inventory are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are often sites of substantial CH_4 emissions from anaerobic sediments.

Canals and ditches (terms are used interchangeably) are linear water features constructed to transport water (i.e. stormwater drainage, aqueduct), to irrigate or drain land, to connect two or more bodies of water, or to serve as a waterway for watercraft. The geometry and construction of canals and ditches varies widely and includes narrow earthen channels (<1m wide) and concrete lined aqueducts in excess of 50m wide. Canals and ditches can be extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds increased by 14 percent from 1990 to 2020 due to freshwater ponds matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land (Table 6-80). Methane emissions from canals and ditches have remained constant throughout the time series. Age data are not available for most canals and ditches, and for this Inventory they were all assumed to be greater than 20 years old in 1990 and therefore included in Flooded Land Remaining Flooded Land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies increased 7 percent between 1990 and 2005 but have since stabilized at 2005 levels (Table 6-80 and Table 6-81).

Table 6-80: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Other constructed waterbodies							
Canals and ditches	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Freshwater ponds	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Total	**1.0**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-81: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Other constructed waterbodies							
Canals and ditches	21.6	21.6	21.6	21.6	21.6	21.6	21.6
Freshwater ponds	19.4	22.0	22.1	22.2	22.2	22.2	22.2
Total	**40.9**	**43.6**	**43.7**	**43.7**	**43.7**	**43.7**	**43.8**

Note: Alaska, Hawaii, and U.S. Territories not included.

States bordering the Gulf of Mexico including Texas, Louisiana, Mississippi, and Florida are the largest source of CH_4 from other constructed waterbodies (Figure 6-13, Table 6-82). Louisiana is the source of over 50 percent of CH_4 emissions from U.S. canals and ditches and Texas is the largest source of CH_4 from freshwater ponds in the United States. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

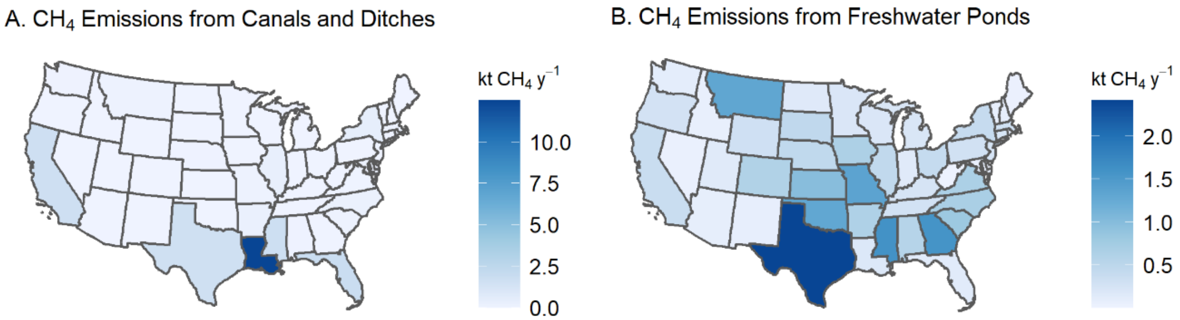
Table 6-82: CH_4 Emissions (kt CH_4) from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020

State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	0.6	0.6
Arizona	+	+	+
Arkansas	+	0.6	0.9
California	1.7	+	2.1
Colorado	+	0.6	0.6
Connecticut	+	+	+
Delaware	+	+	+
District of Columbia	+	+	+
Florida	1.9	+	2.0
Georgia	+	1.6	1.6
Idaho	+	+	+
Illinois	+	+	0.8
Indiana	+	+	+
Iowa	+	0.7	0.7
Kansas	+	1.0	1.0
Kentucky	+	+	+
Louisiana	12.5	+	12.7
Maine	+	+	+
Maryland	+	+	+
Massachusetts	+	+	+
Michigan	+	+	+
Minnesota	+	+	+
Mississippi	1.7	1.6	3.3
Missouri	+	1.4	1.5
Montana	+	1.3	1.4
Nebraska	+	+	0.5
Nevada	+	+	+
New Hampshire	+	+	+
New Jersey	+	+	+
New Mexico	+	+	+
New York	+	+	0.9
North Carolina	+	0.7	0.9
North Dakota	+	+	+
Ohio	+	+	+
Oklahoma	+	1.3	1.3
Oregon	+	+	+
Pennsylvania	+	+	+
Rhode Island	+	+	+
South Carolina	+	0.8	0.9
South Dakota	+	+	+
Tennessee	+	+	+
Texas	1.6	2.4	4.0
Utah	+	+	+
Vermont	+	+	+
Virginia	+	0.7	0.7
Washington	+	+	+
West Virginia	+	+	+
Wisconsin	+	+	+
Wyoming	+	+	+
Total	**21.6**	**22.2**	**43.8**

+ Indicates values less than 0.5 kt

Note: Alaska, Hawaii, and U.S. Territories not included.

Figure 6-13: CH_4 Emissions (kt CH_4) from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020



Methodology and Time-Series Consistency

Estimates of CH_4 emission for other constructed waterbodies in Flooded Land Remaining Flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Based on IPCC guidance, methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-83). Although literature data on greenhouse gas emissions from canals and ditches is relatively sparse, they have the highest default emission factor of all flooded land types (Table 6-83). Default emission factors for freshwater ponds are on the higher end of those for reservoirs. There are insufficient data to support climate specific emission factors for ponds or canals and ditches. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Other Constructed Waterbody	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Freshwater ponds	0.183
Canals and ditches	0.416

Area estimates

Freshwater ponds in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[77] the National Lakes Assessment (NLA)[78] data, the National Inventory of Dams (NID),[79] and the Navigable Waterways (NW)[80] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies in these data sets that were greater than 20 years old, less than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered ponds in Flooded Land Remaining Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the

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[77] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[78] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[79] See https://nid.sec.usace.army.mil.

[80] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about

NID, 4) the water body was deemed “man made” in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the ponds inventory.

Surface areas for ponds and canals/ditches were taken from NHD or the NW. Waterbodies were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[81]) and the final area inventory was screened to ensure no waterbodies were duplicated. While the distribution of U.S. waterbodies <8 ha is well represented in NHD, it is difficult to determine which of these waterbodies are subject to water level management. The presence or absence of a flow control structure associated with these small waterbodies is typically not documented in NHD, thus EPA used the NID for this purpose. The NID only includes dams that pose a hazard if they were to fail, equal or exceed 25 feet in height and exceed 15 acre-feet in storage, or equal or exceed 50 acre-feet storage and exceed 6 feet in height.[82] The extent to which these criteria fail to capture flow control structures associated with freshwater ponds in the United States in unknown, but the freshwater pond area estimates presented here certainly underestimates the surface area of U.S. freshwater ponds. There is a planned improvement to review other data sources or approaches that could more fully capture all managed freshwater ponds in the United States.

All waterbodies identified as “CANAL/DITCH” in the NHDArea layer of the NHD were classified as `canals and ditches`, a subcategory of other constructed waterbodies (IPCC 2019), for this Inventory. This is an underestimate of U.S. canals and ditches, however, because the majority of canal and ditch length is represented as one dimensional flow lines in the NHDFlowline_Network layer of the NHD. While NHD flowlines can be used to estimate length of ditches and canals, they are one-dimensional features and do not provide area estimates. There is a planned improvement to review other data sources for approaches to better capture the surface area of canals/ditches in the United States.

The age of freshwater ponds was derived from NID when available, otherwise they were assumed to be greater than 20 years old throughout the time series. Age data were not available for canals and ditches and they were assumed to be greater than 20 years old in 1990 and therefore included in Flooded Land Remaining Flooded Land throughout the time series. For the year 2020, this Inventory contains 121,255 ha of freshwater ponds and 51,834 ha of canals and ditches in Flooded Land Remaining Flooded Land. The surface area of freshwater ponds increased by 15 percent from 1990 to 2020 due to flooded lands matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land. All canals and ditches were assumed to be greater than 20 years old throughout the time series, thus the surface area of these flooded lands is constant throughout the time series. Overall, the surface area of other constructed waterbodies increased 10 percent between 1990 and 2020, with most of the increase occurring by 2005 (Table 6-84).

Table 6-84: National Surface Area (ha) Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies

	1990	2005	2016	2017	2018	2018	2020
Canals and ditches	51,834	51,834	51,834	51,834	51,834	51,834	51,834
Freshwater ponds	105,859	120,373	121,014	121,067	121,167	121,215	121,255
Total	**157,693**	**172,207**	**172,848**	**172,901**	**173,001**	**173,049**	**173,089**

Note: Alaska, Hawaii, and U.S. Territories not included.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-14A). Louisiana contains over half of all U.S. canal and ditch surface area, most of which was created to drain swamps and wetlands for agricultural production (Davis 1973). Freshwater ponds are more widely distributed across the United States. (Figure 6-14B). Texas has the greatest surface area of freshwater ponds, equivalent to 11 percent of all freshwater pond surface area in the United States. Texas also had the largest increase in freshwater pond surface area during the time series.

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[81] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[82] See https://nid.sec.usace.army.mil.

Figure 6-14: Surface Area (hectares) of Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020

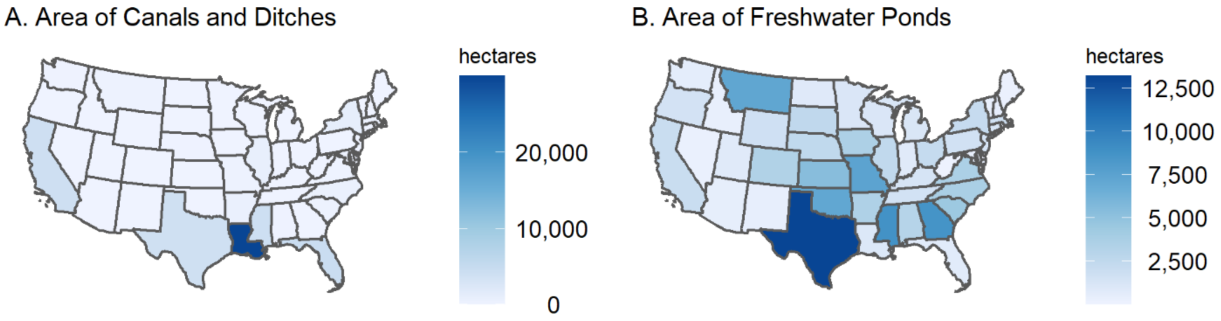

Table 6-85: State Totals of Surface Area (ha) in Flooded Land Remaining Flooded Land—Other Constructed Waterbodies

State	1990	2005	2016	2017	2018	2019	2020
Alabama	3,007	3,244	3,252	3,252	3,255	3,255	3,255
Arizona	459	488	488	488	493	493	493
Arkansas	3,796	4,051	4,051	4,051	4,051	4,051	4,051
California	6,022	6,106	6,120	6,120	6,120	6,122	6,122
Colorado	3,227	3,367	3,381	3,381	3,390	3,390	3,390
Connecticut	1,180	1,226	1,226	1,226	1,226	1,226	1,226
Delaware	481	488	488	488	488	488	488
District of Columbia	6	6	6	6	6	6	6
Florida	5,169	5,214	5,225	5,225	5,225	5,228	5,228
Georgia	8,069	8,673	8,687	8,687	8,687	8,687	8,687
Idaho	389	433	433	433	433	433	433
Illinois	2,998	3,318	3,344	3,345	3,350	3,350	3,350
Indiana	756	836	843	843	843	843	843
Iowa	2,529	3,574	3,596	3,596	3,596	3,600	3,607
Kansas	3,724	5,357	5,381	5,388	5,404	5,411	5,411
Kentucky	1,143	1,327	1,327	1,330	1,330	1,330	1,330
Louisiana	30,900	30,991	30,995	30,995	30,995	30,995	30,995
Maine	224	243	247	247	247	247	247
Maryland	574	609	615	615	615	615	615
Massachusetts	1,813	1,871	1,897	1,902	1,908	1,912	1,919
Michigan	1,082	1,172	1,183	1,185	1,185	1,185	1,185
Minnesota	1,042	1,133	1,137	1,137	1,137	1,137	1,151
Mississippi	12,445	12,852	12,874	12,888	12,888	12,893	12,901
Missouri	5,312	7,684	7,700	7,700	7,700	7,700	7,700
Montana	7,113	7,411	7,411	7,411	7,411	7,416	7,416
Nebraska	1,844	2,590	2,605	2,605	2,630	2,630	2,630
Nevada	242	242	260	262	262	262	262
New Hampshire	451	497	517	517	517	517	517
New Jersey	1,381	1,396	1,396	1,396	1,399	1,399	1,399
New Mexico	444	453	453	453	453	453	453
New York	3,071	3,232	3,294	3,294	3,294	3,294	3,294
North Carolina	3,977	4,178	4,216	4,216	4,216	4,216	4,218
North Dakota	784	837	866	866	873	873	873
Ohio	2,008	2,201	2,229	2,238	2,238	2,238	2,238
Oklahoma	6,138	7,139	7,162	7,162	7,165	7,172	7,172
Oregon	1,448	1,520	1,533	1,533	1,536	1,536	1,536
Pennsylvania	1,483	1,610	1,630	1,630	1,631	1,631	1,631

Rhode Island	257	258	258	258	258	258	258
South Carolina	4,172	4,617	4,638	4,640	4,640	4,640	4,642
South Dakota	2,403	2,500	2,537	2,539	2,539	2,548	2,548
Tennessee	1,372	1,562	1,569	1,569	1,576	1,579	1,579
Texas	14,634	17,052	17,082	17,086	17,090	17,091	17,091
Utah	784	829	829	829	829	829	829
Vermont	311	368	372	372	372	372	372
Virginia	3,549	3,721	3,721	3,721	3,721	3,721	3,721
Washington	653	727	759	759	761	761	761
West Virginia	124	124	124	124	124	124	124
Wisconsin	1,009	1,158	1,170	1,170	1,170	1,170	1,170
Wyoming	1,693	1,721	1,721	1,721	1,721	1,721	1,721
Total	**157,693**	**172,207**	**172,848**	**172,901**	**173,001**	**173,049**	**173,089**

Note: Alaska, Hawaii, and U.S. Territories not included.

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in Flooded Land Remaining Flooded Land (Table 6-86) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of +/-15 percent for the flooded land area estimates is assumed and is based on expert judgment. These uncertainties do not include the underestimate of pond and canal/ditch surface areas discussed above, see Planned Improvements for a discussion on steps being taken to improve the area estimates.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Canals and ditches	CH_4	0.54	0.45	0.62	-15.9%	15.8%
Freshwater pond	CH_4	0.55	0.55	0.56	-0.3%	0.3%
Total	**CH_4**	**1.09**	**1.01**	**1.18**	**-8%**	**7.9%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[83] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

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[83] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

EPA is unaware of ongoing work that could be used to develop country-specific emission factors for Other Constructed Waterbodies but is working to improve land use representation of canals and ditches. Canals and ditches are represented as both flow lines and area polygons in NHD. The area polygons are used in this Inventory, but flow lines only contain the length of the feature and therefore cannot be directly used to calculate surface area. EPA is researching methods for associating flow lines with a width, which would enable the area calculations needed for the Inventory.

Canal and ditch surface area included here may overlap with ditches and canals included in CH_4 emission estimates for ditches draining inland organic soils (IPCC 2013, section 2.2.2.1). EPA plans to reconcile ditch/canal surface areas between the two managed land types (flooded land vs drained inland organic soils) in the next (i.e., 1990 through 2021) Inventory.

U.S. waterbodies less than 8 ha are well represented in NHD, but the presence or absence of water level control structures associated with these small waterbodies is not well documented in national data sources. To improve the representation of managed ponds in future Inventories, EPA will attempt to locate state or county records on small dam construction permits and/or inspection records to supplement records in the NID. EPA will also use surrounding land use as a proxy for management. For example, a pond surrounded by cultivated land is likely subject to water level management and should be included in the inventory. Even if the pond were not subject to water level management, greenhouse gas emissions from the system are likely enhanced by elevated nutrient and sediment inputs from the surrounding managed lands, thus the emissions should be considered anthropogenic and included in the inventory.

Hawaii, Alaska, and U.S. Territories will be included in the (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[84] an enhanced version of the NHD used in this Inventory.

6.9 Land Converted to Wetlands (CRF Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land Converted to Vegetated Coastal Wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. All other land

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[84] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

categories (i.e., Forest Land, Cropland, Grassland, Settlements and Other Lands) are identified as having some area converting to Vegetated Coastal Wetlands. Between 1990 and 2020 the rate of annual transition for *Land Converted to Vegetated Coastal Wetlands* ranged from 0 to 2,650 ha per year, depending on the type of land converted.[85] Conversion rates from Forest Land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[86] Little to no conversion of Cropland, Grassland, Settlement, or Other Lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.

At the present stage of Inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the Land Representation (NOAA OCM 2020).

In this Inventory, biomass, dead organic material (DOM) and soil C stock changes as well as CH_4 emissions are quantified as a result of the land use conversion to coastal wetlands and the land is assumed to be held in this category for up to 20 years after which it is classified as *Coastal Wetlands Remaining Coastal Wetlands*. Estimates of emissions and removals are based on emission factor data that have been applied to assess changes in each respective flux for *Land Converted to Vegetated Coastal Wetlands*. Following conversion to Vegetated Coastal Wetlands, it is assumed there is a loss of biomass C stocks from the converted Forest Land, Cropland and Grassland and as well as the loss of DOM C stocks from Forest Land. Converted lands are held in this land category for up to 20 years and the assumption is that the C stock losses from biomass and DOM all occur in the year of conversion. There are no soil C losses from land use conversion. Carbon stock increases in coastal wetlands as a result of gains in plant biomass and DOM on these converted lands are also included during the year of transition even though the entire C stock accrual takes many years to occur. Soil C accumulation and CH_4 emissions are quantified using an annual rate in this Inventory and thus are occurring over the period under which lands are held in this category; therefore, the soil C removals and CH_4 emissions presented for a given year include the cumulative removals/emissions for the new area that was converted during that year and the area held in this category for the prior 19 years. At salinities less than half that of seawater, the transition from upland dry soils to wetland soils results in CH_4 emissions. The United States calculates emissions and removals based upon stock change.

Conversion to coastal wetlands resulted in a biomass C stock loss of 0.1 MMT CO_2 Eq. (0.03 MMT C) in 2020 (Table 6-87 and Table 6-88). Loss of forest biomass through conversion of Forest Lands to Vegetated Coastal Wetlands is the primary driver behind biomass C stock change being a source rather than a sink across the time series. Conversion of Cropland, Grassland, Settlement and Other Lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.03 MMT CO_2 Eq. (0.008 MMT C) in 2020 (Table 6-87 and Table 6-88), which is driven by the loss of DOM when Forest Land is converted to Vegetated Coastal Wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of Cropland, Grassland, Settlement and Other Land results in a net increase in DOM. Once Tier 1 or 2 DOM values are collated and accounted for in estuarine and palustrine scrub shrub coastal wetlands and estuarine forested wetlands (in climates other than subtropical), the carbon emissions will decrease. Across all time periods, soil C accumulation resulting from *Lands Converted to Vegetated Coastal Wetlands* is a carbon sink and has ranged between -0.2 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-87 and Table 6-88). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (6.7 kt CH_4) in 2020 (Table 6-89). Methane emissions due to the conversion of *Lands to Vegetated Coastal Wetlands* are largely the result of Forest Land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2001 (0.2 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels.

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[85] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed August 2021.

[86] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the Inventory.

Table 6-87: Net CO_2 Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(0.02)**	**(0.01)**	**+**	**0.01**	**0.02**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.11	0.12	0.03	0.03	0.03	0.03	0.03
Soil C Stock	(0.23)	(0.24)	(0.18)	(0.17)	(0.16)	(0.15)	(0.14)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.11**	**0.12**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.19)**	**(0.18)**	**(0.18)**	**(0.17)**	**(0.16)**
Total Flux	**0.46**	**0.47**	**(0.04)**	**(0.03)**	**(0.01)**	**(0.02)**	**(+)**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration

Table 6-88: Net CO_2 Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT C)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**(0.00)**	**(+)**	**+**	**+**	**0.01**
Biomass C Stock	0.17	0.17	0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03	0.03	0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)	(0.06)	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**	**0.16**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**

Total Dead Organic Matter Flux	**0.03**	**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**	**(0.07)**	**(0.05)**	**(0.05)**	**(0.05)**	**(0.05)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(0.01)**	**(0.01)**	**(0.01)**	**(+)**	**(+)**

+ Absolute value does not exceed 0.005 MMT C.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-89: CH_4 Emissions from *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	+	0.01	0.04	0.04	0.04	0.04	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.25	0.24	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	7.60	7.22	6.85	6.48	6.10
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.05	0.06	0.07	0.07	0.08
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.01
CH_4 Emissions (kt CH_4)	0.08	0.14	0.37	0.40	0.43	0.47	0.50
Settlements Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	+	+	+	+	+	+
Total CH_4 Emissions (MMT CO_2 Eq.)	**0.25**	**0.25**	**0.20**	**0.19**	**0.18**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**8.05**	**7.72**	**7.39**	**7.06**	**6.73**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq. or 0.005 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil C stocks and CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Biomass C stocks for *Land Converted to Vegetated Coastal Wetlands* are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating Vegetated Coastal Wetlands from ephemerally flooded upland Grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets using the C-CAP change data closest in date to a given year. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[87]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014), and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass C stocks for Forest Land, Cropland, and Grassland that are lost with the conversion to *Vegetated Coastal Wetlands* were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass C stock values of each land use category (i.e., Forest Land, Cropland, and Grassland) from those of *Vegetated Coastal Wetlands* in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass C stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for *Lands Converted to Vegetated Coastal Wetlands* across all years. Tier 1 estimates of mangrove DOM C stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for Forest Land converted to Vegetated Coastal Wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to negligible for other land use conversions (i.e., other than Forest Land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the difference between Tier 1 DOM C stocks for Vegetated Coastal Wetlands and Forest Land. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil C removals are estimated for *Land Converted to Vegetated Coastal Wetlands* across all years. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). To estimate soil C stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC (2014) guidance, *Land Converted to Vegetated Coastal Wetlands* is assumed to remain in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Tier 2 level estimates of soil C stock changes associated with annual soil C accumulation from *Land Converted to Vegetated Coastal Wetlands* were developed using country-specific soil C removal factors multiplied by activity data of land area for *Land Converted to Vegetated Coastal Wetlands* for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil C accumulation to be

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[87] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2020.

instantaneously equivalent to that in natural settings and that soil C accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2020 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement* (IPCC 2014), and is applied to the area of *Land Converted to Vegetated Coastal Wetlands* on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement*. Because *Land Converted to Vegetated Coastal Wetlands* is held in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining to Vegetated Coastal Wetlands,* CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty

Underlying uncertainties in estimates of soil C removal factors, biomass change, DOM, and CH_4 emissions include error in uncertainties associated with Tier 2 literature values of soil C removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass C removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil C stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-90 for each carbon pool and the CH_4 emissions. The combined uncertainty is +/-42.2 percent. In 2020, the total flux was 0.16 MMT CO_2 Eq., with lower and upper estimates of 0.09 and 0.23 MMT CO_2 Eq.

Table 6-90: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes occurring within *Land Converted to Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.12	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.03	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.16)	(0.2)	(0.1)	-17.8%	17.8%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.16**	**0.09**	**0.23**	**-42.2%**	**42.2%**

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads. Biomass C stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads prior to inclusion in the inventory and from IPCC reports. As a QC step, a check was undertaken confirming that Coastal Wetlands recognized by C-CAP represent a subset of Wetlands recognized by the NRI for marine coastal states. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil C stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stocks and biomass for coastal wetlands.[88] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent changes in soil C stocks and will be incorporated into the next (i.e., 2023) Inventory submission.

Currently, the only coastal wetland conversion that is reported in the Inventory is *Lands Converted to Vegetated Coastal Wetlands*. The next (2023) submission will include C stock change data for *Lands Converted to Unvegetated Open Water Coastal Wetlands*.

Land Converted to Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural production of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation but would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as “reservoirs” or “other constructed waterbodies” (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of “other constructed waterbodies” including freshwater ponds and canals/ditches.

Land that has been flooded for 20 years or greater is defined as Flooded Land Remaining Flooded Land and land flooded for less than 20 years is defined as Land Converted to Flooded Land. The distinction is based on literature reports that CO_2 and CH_4 emissions are high immediately following flooding as labile organic matter is rapidly degraded but decline to a steady background level approximately 20 years after flooding. Both CO_2 and CH_4 emissions are inventoried for Land Converted to Flooded Land.

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[88] See https://serc.si.edu/coastalcarbon; accessed August 2021.

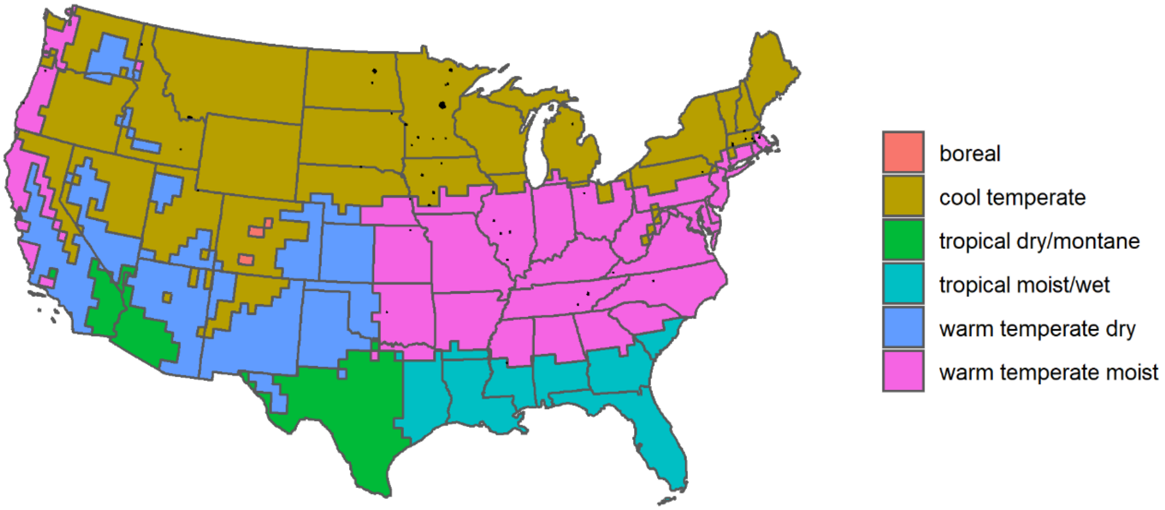
Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not inventoried here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Volume 4, Chapter 11, *2006 IPCC Guidelines*) and wastewater management (Volume 5, Chapter 6, *2006 IPCC Guidelines*).

Emissions from Land Converted to Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a “drawdown zone” or “inundation area.” Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2020 the conterminous United States hosted 74,292 hectares of reservoir surface area in Land Converted to Flooded Land (see Methodology and Time-Series Consistency below for calculation details) distributed across four of the six aggregated climate zones used to define flooded land emission factors (Figure 6-15) (IPCC 2019). Alaska, Hawaii, and U.S. Territories are not included in this report due to a lack of data (see the Methodology and Time-Series Consistency section).

Figure 6-15: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2020



Note: Colors represent climate zone used to derive IPCC default emission factors.

Methane and CO_2 are produced in reservoirs through the natural breakdown of organic matter. Per unit area emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae). Greenhouse gases produced in reservoirs can be emitted directly from the water surface and inundation areas or as greenhouse gas-enriched water passes through the dam and the downstream river. Sufficient information exists to estimate downstream CH_4 emissions using Tier 1 IPCC guidance (IPCC 2019), but no guidance is provided for downstream CO_2 emissions. Table 6-91 and Table 6-92 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs and associated inundation areas in Land Converted to Flooded Land. The decrease in CO_2

and CH_4 emissions through the time series is attributable to reservoirs matriculating from the Land Converted to Flooded Land category into the Flooded Land Remaining Flooded Land Category. Emissions have been stable since 2005, reflecting the low rate of new flooded land creation over the past 15 years.

Table 6-91: CH_4 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**2.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Surface Emissions	2.1	0.2	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Inundation Areas	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Surface Emissions	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Downstream Emissions	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**2.5**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-92: CH_4 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**93**	**8**	**7**	**7**	**7**	**7**	**7**
Surface Emissions	86	7	6	6	6	6	6
Downstream Emissions	8	1	1	1	1	1	1
Inundation Areas	**7**	**0**	**0**	**0**	**0**	**0**	**0**
Surface Emissions	6	0	0	0	0	0	0
Downstream Emissions	1	0	0	0	0	0	0
Total	**100**	**8**	**7**	**7**	**7**	**7**	**7**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-93: CO_2 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoir	3.5	0.3	0.3	0.3	0.3	0.3	0.3
Inundation Area	0.3	+	+	+	+	+	+
Total	**3.8**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+Indicates values less than 0.05 MMT CO_2

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-94: CO_2 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoir	1.0	0.1	0.1	0.1	0.1	0.1	0.1
Inundation Area	0.1	+	+	+	+	+	+
Total	**1.0**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+Indicates values less than 0.05 MMT C

Note: Alaska, Hawaii, and U.S. Territories are not included.

Methane and CO_2 emissions from reservoirs and inundated areas in Minnesota were nearly 5 and 10-fold greater than any other state, respectively (Figure 6-16 and Table 6-95). This is attributed to nine dams built in Minnesota after 2001 which impound 58,875 ha of water, 88 percent of which is located in Mille Lacs lake. North Dakota is the second largest source of CO_2 and CH_4 from reservoirs and inundated areas in Land Converted to Flooded Land. Ninety five percent of Land Converted to Flooded Land reservoir surface area in North Dakota is attributed to Devils Lake. Both Mille Lacs and Devils Lakes are natural waterbodies provisioned with dams for water level management.

Figure 6-16: 2020 A) CH_4 and B) CO_2 Emissions from U.S. Reservoirs and Inundation Areas in Land Converted to Flooded Land

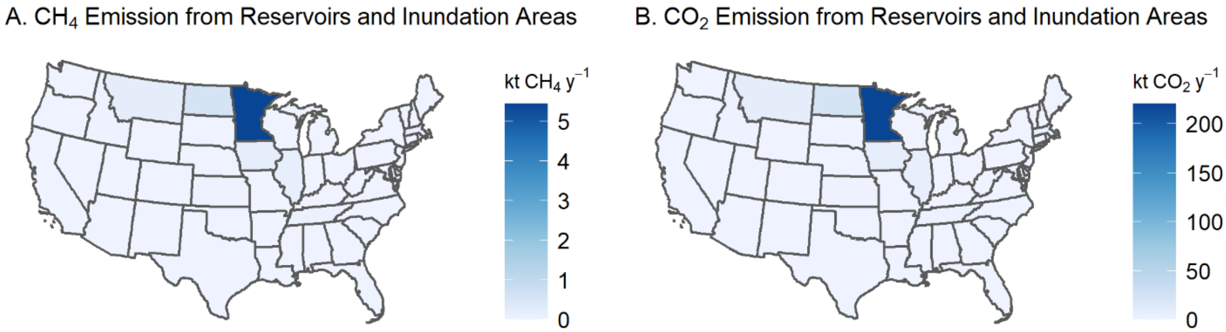


Table 6-95: Methane and CO_2 Emissions (kt) from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land in 2020

	Reservoir			Inundation Area			Total		
	CH_4		CO_2[a]	CH_4		CO_2[a]	CH_4		CO_2[a]
State	Downstream	Surface	Surface	Downstream	Surface	Surface	Downstream	Surface	Surface
Alabama	0	0	0	0	0	0	0	0	0
Arizona	0	0	0	0	0	0	0	0	0
Arkansas	0	0	0	0	0	0	0	0	0
California	+	+	+	0	0	0	+	+	+
Colorado	+	+	+	0	0	0	+	+	+
Connecticut	+	+	+	0	0	0	+	+	+
Delaware	0	0	0	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0	0	0
Florida	0	0	0	0	0	0	0	0	0
Georgia	0	0	0	0	0	0	0	0	0
Idaho	+	+	1	0	0	0	+	+	1
Illinois	+	+	6	0	0	0	+	+	6
Indiana	0	0	0	0	0	0	0	0	0
Iowa	+	+	8	0	0	0	+	+	8
Kansas	+	+	1	0	0	0	+	+	1
Kentucky	0	0	0	0	0	0	0	0	0
Louisiana	+	+	+	0	0	0	+	+	+
Maine	+	+	+	0	0	0	+	+	+
Maryland	0	0	0	0	0	0	0	0	0
Massachusetts	+	+	5	0	0	0	+	+	5
Michigan	+	+	+	0	0	0	+	+	+
Minnesota	+	5	215	+	+	5	+	5	220
Mississippi	+	+	+	0	0	0	+	+	+
Missouri	0	0	0	0	0	0	0	0	0
Montana	+	+	7	+	+	3	+	+	9
Nebraska	+	+	+	0	0	0	+	+	+
Nevada	+	+	+	0	0	0	+	+	+
New Hampshire	+	+	1	0	0	0	+	+	1
New Jersey	0	0	0	0	0	0	0	0	0
New Mexico	+	+	+	0	0	0	+	+	+
New York	+	+	+	0	0	0	+	+	+
North Carolina	+	+	1	0	0	0	+	+	1
North Dakota	+	1	23	0	0	0	+	1	23
Ohio	+	+	+	0	0	0	+	+	+

Oklahoma	+	+	+	0	0	0	+	+	+
Oregon	+	+	1	0	0	0	+	+	1
Pennsylvania	+	+	+	0	0	0	+	+	+
Rhode Island	0	0	0	0	0	0	0	0	0
South Carolina	0	0	0	0	0	0	0	0	0
South Dakota	+	+	+	0	0	0	+	+	+
Tennessee	+	+	3	0	0	0	+	+	3
Texas	+	+	+	0	0	0	+	+	+
Utah	+	+	+	0	0	0	+	+	+
Vermont	0	0	0	0	0	0	0	0	0
Virginia	+	+	+	0	0	0	+	+	+
Washington	+	+	+	0	0	0	+	+	+
West Virginia	0	0	0	0	0	0	0	0	0
Wisconsin	0	0	0	0	0	0	0	0	0
Wyoming	0	0	0	0	0	0	0	0	0

+ Indicates values less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the Inventory.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs and associated inundation areas in Land Converted to Flooded Land follow the Tier 1 methodology in the IPCC guidance (IPCC 2019). All calculations are performed at the state level and summed to obtain national estimates. Emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate specific emission factor (Table 6-96). Downstream CH_4 emissions are calculated as 9 percent of the surface CH_4 emission (Tier 1 default). The IPCC guidance (IPCC 2019) does not address downstream CO_2 emissions, presumably because there are insufficient data in the literature to estimate this emission pathway.

The IPCC default surface emission factors are derived from model predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zone are present in the conterminous United States.

Table 6-96: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land

	Surface emission factor	
Climate	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Boreal	0.0277	3.45
Cool Temperate	0.0847	3.74
Warm Temperate Dry	0.1956	6.23
Earm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Area Estimates

Reservoirs in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[89] the National Lakes Assessment (NLA)[90] data, the National

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[89] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[90] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

Inventory of Dams (NID),[91] and the Navigable Waterways (NW)[92] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies less than 20 years old, greater than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered reservoirs in Land Converted to Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the flooded land inventory. Surface areas for identified flooded lands were taken from NHD or the NW.

IPCC (2019) allows for the exclusion of reservoirs from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area or water residence time was substantially altered by their associated dams. EPA assumes that all other waterbodies identified through the six criteria described above were substantially impacted by the construction of dams.

EPA assumes that all reservoirs included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Reservoir age was determined from the year the dam was completed as reported in the NID (available for 40,012 out of 54,670 reservoirs). When dam completion year was not available, the reservoir was assumed to be greater than 20 years old. Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[93]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the inventory. Surface areas for reservoirs and associated inundation areas were taken from NHD or the NW and the final inventory of reservoirs and associated inundation areas was screened to ensure no waterbodies were duplicated.

Many reservoirs are surrounded by land that is dry for a portion of the year but is periodically flooded when water inflows to the reservoir exceed outflows and the reservoir surface area expands into surrounding lands. This can occur for a variety of reasons including high rates of water runoff from the watershed (i.e., snow melt, large precipitation events), deliberate efforts to raise water levels for seasonal recreation or wildlife habitat, and management efforts to reduce inflows to downstream systems. These periodically flooded lands are represented as "Inundation Areas" in the NHDArea layer (Figure 6-17). Inundation areas are considered equivalent to "drawdown zones" in IPCC (2019) and CO_2 and CH_4 emissions from these lands are estimated using the same methodology as for reservoirs.

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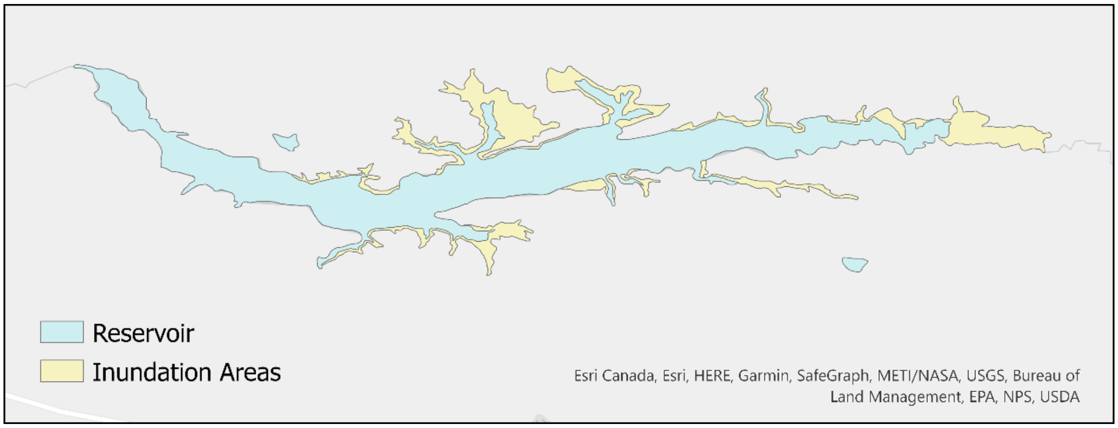
[91] See https://nid.sec.usace.army.mil.

[92] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[93] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

Figure 6-17: Example of a Reservoir and Associated Inundation Area in Land Converted to Flooded Land



Esri Canada, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA

The surface area of reservoirs and inundation areas in Land Converted to Flooded Land decreased by approximately 90 percent from 1990 to 2020 (Table 6-97). This is due to reservoirs that were less than 20 years old at beginning of time series entering the Flooded Land Remaining Flooded Land category when they reached 20 years of age. The rate at which flooded land has aged out of the Land Converted to Flooded Land category has outpaced the rate of new dam construction. New dam construction has slowed considerably during the time series with no new dams entering the inventory since 2017 (Figure 6-18).

Lakes Sakakawea and Oahe in North Dakota and South Dakota are notable examples of reservoirs that matriculated out of Land Converted to Flooded Land during the time series. These Missouri River impoundments have a combined surface area in excess of 0.25 million hectares and aged out of Land Converted to Flooded Land between 2000 and 2003, but in 2020 North Dakota still had the second largest expanse of surface area in this category due primarily to a new dam on Devils Lake.

Table 6-97: National Totals of Reservoir and Associated Inundation Areas Surface Area (thousands of ha) in Land Converted to Flooded Land

Surface Area (thousands of ha)	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Reservoir	699	75	74	73	73	72	72
Inundation Area	51	3	2	2	2	2	2

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-18: Number of dams built per year from 1990-2020

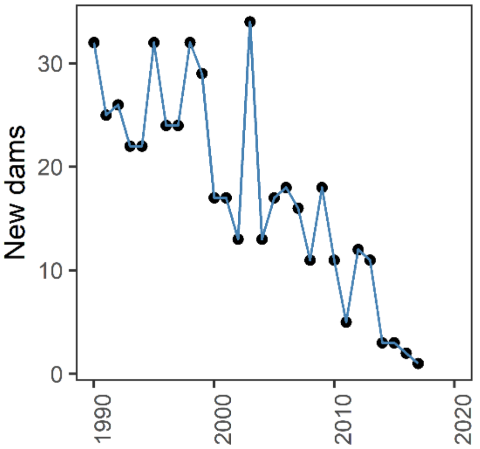


Table 6-98: State breakdown of Reservoirs and Associated Inundation Area Surface Area (thousands of ha) in Land Converted to Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	32.3	0.1	0.0	0.0	0.0	0.0	0.0
Arizona	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	32.1	0.0	0.0	0.0	0.0	0.0	0.0
California	10.7	0.5	0.4	0.4	0.4	0.1	0.0
Colorado	5.8	0.1	0.1	0.1	0.1	0.1	0.1
Connecticut	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	10.4	0.2	0.0	0.0	0.0	0.0	0.0
Georgia	10.2	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	10.1	0.8	0.4	0.4	0.4	0.4	0.4
Illinois	19.6	3.1	1.3	1.2	1.2	1.1	1.1
Indiana	6.2	2.3	0.0	0.0	0.0	0.0	0.0
Iowa	11.4	1.9	2.1	2.1	2.1	2.1	2.1
Kansas	26.7	0.4	0.3	0.3	0.2	0.2	0.2
Kentucky	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Louisiana	16.9	3.0	0.0	0.0	0.0	0.0	0.0
Maine	13.2	3.4	0.1	0.1	0.1	0.1	0.1
Maryland	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Massachusetts	1.0	0.6	1.3	1.3	1.3	1.2	1.2
Michigan	12.8	2.7	0.1	0.1	0.1	0.1	0.1
Minnesota	9.0	9.1	59.7	58.9	58.9	58.9	58.9
Mississippi	6.0	0.1	0.0	0.0	0.0	0.0	0.0
Missouri	56.7	0.0	0.0	0.0	0.0	0.0	0.0
Montana	8.5	3.8	2.5	2.5	2.5	2.5	2.5
Nebraska	5.5	1.3	0.2	0.2	0.2	0.2	0.1
Nevada	1.3	0.3	0.0	0.0	0.0	0.0	0.0
New Hampshire	0.4	0.2	0.2	0.2	0.2	0.2	0.2
New Jersey	0.3	0.0	0.0	0.0	0.0	0.0	0.0
New Mexico	0.2	0.0	0.0	0.0	0.0	0.0	0.0
New York	2.4	0.9	0.1	0.1	0.1	0.1	0.1
North Carolina	19.2	0.5	0.1	0.1	0.1	0.1	0.1
North Dakota	159.4	2.5	6.7	6.2	6.2	6.2	6.2

Ohio	3.1		0.0		0.0	0.0	0.0	0.0	0.0
Oklahoma	19.6		0.2		0.0	0.0	0.0	0.0	0.0
Oregon	3.9		0.2		0.2	0.2	0.1	0.1	0.1
Pennsylvania	3.2		0.3		0.3	0.3	0.1	0.1	0.1
Rhode Island	0.2		0.0		0.0	0.0	0.0	0.0	0.0
South Carolina	6.0		0.0		0.0	0.0	0.0	0.0	0.0
South Dakota	106.5		0.0		0.0	0.0	0.0	0.0	0.0
Tennessee	2.7		0.0		0.6	0.6	0.6	0.6	0.6
Texas	49.5		0.1		0.0	0.0	0.0	0.0	0.0
Utah	43.0		37.0		0.0	0.0	0.0	0.0	0.0
Vermont	0.1		0.1		0.0	0.0	0.0	0.0	0.0
Virginia	5.8		0.0		0.0	0.0	0.0	0.0	0.0
Washington	3.0		0.2		0.0	0.0	0.0	0.0	0.0
West Virginia	2.9		1.6		0.0	0.0	0.0	0.0	0.0
Wisconsin	1.9		0.4		0.0	0.0	0.0	0.0	0.0
Wyoming	9.1		0.3		0.0	0.0	0.0	0.0	0.0
Total	**750.0**		**78.5**		**76.7**	**75.3**	**75.0**	**74.5**	**74.3**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Uncertainty

Uncertainty in estimates of CH_4 and CO_2 emissions from reservoirs on Land Converted to Flooded Land were developed using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory (Table 6-99). Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ±15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-99: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	0.2	0.1	0.2	-12.7%	12.5%
Surface	CO_2	0.3	0.2	0.3	-13.4%	13.5%
Downstream	CH_4	+	+	0.1	-57.1%	287.3
Inundation Area						
Surface	CH_4	+	+	+	-13.1%	12.9%
Surface	CO_2	+	+	+	-13.0%	14.1%
Downstream	CH_4	+	+	+	-56.9%	290.7%
Total		**0.5**	**0.4**	**0.5**	**-13.1%**	**16.0%**

+ Indicates values less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes

Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[94] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

EPA is measuring greenhouse gas emissions from 108 flooded lands (reservoirs) in the conterminous United States. The survey will be complete by September 2023 and the data will be used to predict greenhouse gas emission rates for all U.S. flooded lands. The Inventory will be updated at that time using these country-specific emission factors developed through the measurement campaign.

Hawaii, Alaska and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[95] an enhanced version of the NHD used in this Inventory.

To verify that waterbodies contained in NW are subject to water level management, EPA will overlay the NW with other spatial datasets of water control structures including the inventory of U.S. Army Corps of Engineers locks for water navigation[96] and dams/weirs contained in the NHDPlus HighRes.

Emissions from Land Converted to Flooded Land–Other Constructed Waterbodies

Freshwater ponds are the only type of flooded lands within the "other constructed waterbodies" subcategory of Land Converted to Flooded Land that are included in this Inventory (see Methodology for details). IPCC (2019) describes ponds as waterbodies that are "…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture." The IPCC "Decision tree for types of Flooded Land" (IPCC 2019, Fig. 7.2) elaborates on this description by defining waterbodies less than 8 ha as a subset of "other constructed waterbodies." For this inventory, ponds are defined as managed flooded land not flagged as "canal/ditch" in the NHD (see Methods below) with surface area less than 8 ha. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emission rates than the latter. Activity data on pond salinity is not uniformly available for the conterminous United States and all ponds in Land Converted to Flooded Land are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are sites of substantial CH_4 and CO_2 emissions from anaerobic sediments.

Methane and CO_2 emissions from freshwater ponds decreased 98 percent from 1990 to 2020 due to flooded land matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land. Much of this decline occurred by 2000, but declines have continued through 2020. In 2020, Massachusetts, Mississippi, and Kansas

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[94] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[95] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

[96] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::locks/about.

have the greatest CO_2 and CH_4 emissions for freshwater ponds in Land Converted to Flooded Land (Table 6-100 through Table 6-104, Figure 6-19).

Table 6-100: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-101: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	3	+	+	+	+	+	+

+ Indicates values less than 0.5 kt

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-102: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.5 MMT CO_2 Eq.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-103: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.02	+	+	+	+	+	+

+ Indicates values less than 0.005 MMT C

Note: Alaska, Hawaii, and U.S. Territories are not included.

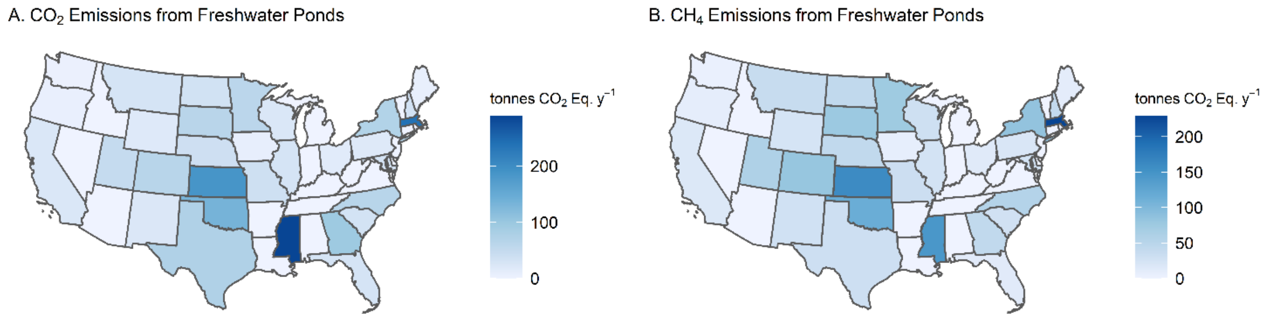
Table 6-104: CH_4 and CO_2 Emissions (MT CO_2 Eq.) from Other Constructed Waterbodies in Land Converted to Flooded Land in 2020

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	0	0	0
Arizona	0	0	0
Arkansas	0	0	0
California	18	25	43
Colorado	82	65	147
Connecticut	0	0	0
Delaware	0	0	0
District of Columbia	0	0	0
Florida	14	30	44
Georgia	43	96	139
Idaho	0	0	0
Illinois	26	31	57
Indiana	0	0	0
Iowa	8	10	18
Kansas	160	187	347
Kentucky	0	0	0
Louisiana	0	0	0
Maine	11	9	19
Maryland	26	31	57

Massachusetts	229	239	468
Michigan	0	0	0
Minnesota	75	61	137
Mississippi	146	288	434
Missouri	33	38	71
Montana	37	30	68
Nebraska	43	39	82
Nevada	0	0	0
New Hampshire	41	34	75
New Jersey	0	0	0
New Mexico	29	24	53
New York	85	72	157
North Carolina	56	65	121
North Dakota	43	35	78
Ohio	14	16	30
Oklahoma	115	135	250
Oregon	9	7	16
Pennsylvania	21	20	40
Rhode Island	0	0	0
South Carolina	28	33	60
South Dakota	78	64	142
Tennessee	0	0	0
Texas	32	75	107
Utah	60	49	109
Vermont	0	0	0
Virginia	0	0	0
Washington	5	5	10
West Virginia	0	0	0
Wisconsin	30	25	55
Wyoming	24	19	43
Total	**1,619**	**1,857**	**3,477**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-19: CH_4 and CO_2 Emissions (MT CO_2 Eq.) from Other Constructed Waterbodies in Land Converted to Flooded Land in 2020



Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for other constructed waterbodies in Land Converted to Flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Greenhouse gas emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-105). Due to a lack of empirical data on CO_2 emissions from recently created ponds, IPCC (2019) states "For all types of ponds created by damming, the methodology described above to estimate CO_2 emissions from land converted to reservoirs may be used." This

Inventory uses IPCC default CO_2 emission factors for land converted to reservoirs when estimating CO_2 emissions from land converted to freshwater ponds. IPCC guidance also states that "there is insufficient information available to derive separate CH_4 emission factors for recently constructed ponds…" and allows for the use of IPCC default CH_4 emission factors for land remaining flooded land. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-105: IPCC Default Methane and CO_2 Emission Factors for Other Constructed Waterbodies in Land Converted to Flooded Land

		Emission Factor	
Other Constructed Waterbody	**Climate Zone**	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Freshwater ponds	Boreal	0.183	3.45
Freshwater ponds	Cool Temperate	0.183	3.74
Freshwater ponds	Warm Temperate Dry	0.183	6.23
Freshwater ponds	Warm Temperate Moist	0.183	5.35
Freshwater ponds	Tropical Dry/Montane	0.183	10.82
Freshwater ponds	Tropical Moist/Wet	0.183	10.16

Area estimates

Freshwater ponds in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[97] the National Lakes Assessment (NLA)[98] data, the National Inventory of Dams (NID),[99] and the Navigable Waterways (NW)[100] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory.

Waterbodies less than 20 years old, less than 8 Ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered ponds in Land Converted to Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the flooded land inventory. Flooded lands that met any one of these criteria and 1) had a surface area less than 8 ha and 2) were not classified as CANALS/DITCHES in the NHD, were classified as freshwater ponds, a subcategory of other constructed waterbodies (IPCC 2019).

Surface areas for ponds were taken from NHD or the NW. Waterbodies were further disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[101]) and the final area inventory was screened to ensure no waterbodies were duplicated.

While the distribution of U.S. waterbodies <8 ha is well represented in NHD, it is difficult to determine which of these waterbodies are subject to water level management. The presence or absence of a flow control structure associated with these small waterbodies is typically not documented in NHD, thus EPA used the NID for this purpose. The NID only includes dams that pose a hazard if they were to fail, equal or exceed 25 feet in height and exceed 15 acre-feet in storage, or equal or exceed 50 acre-feet storage and exceed 6 feet in height.[102] The extent

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[97] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[98] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[99] See https://nid.sec.usace.army.mil.

[100] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[101] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[102] See https://nid.sec.usace.army.mil.

to which these criteria fail to capture flow control structures associated with freshwater ponds in the United States in unknown, but the freshwater pond area inventory presented here is an underestimate. There is a planned improvement to review other data sources or approaches that could more fully capture all managed freshwater ponds in the United States.

IPCC (2019) provides guidance for estimating CH_4 emissions from canals and ditches, a subcategory of other constructed waterbodies, in Land Converted to Flooded Land. While U.S. canals and ditches can be identified in the data sources described above, the age of these systems cannot. EPA assumes that all U.S. canals and ditches are greater than 20 years old and therefore are not included in Land Converted to Flooded Land.

For the year 2020, this Inventory contains 354 ha of freshwater ponds in Land Converted to Flooded Land. The surface area of freshwater ponds decreased by 98 percent from 1990 to 2020 due to flooded lands aging out of Land Converted to Flooded Land more quickly than new flooded lands entered the category. The greatest reduction in freshwater pond surface area occurred in Texas, Missouri, and Kansas (Table 6-107). Freshwater ponds in the 2020 inventory are most abundant in Massachusetts, Kansas, and Mississippi, but show no overarching geographical pattern (Figure 6-20).

Table 6-106: National Surface Area (ha) Totals of Other Constructed Waterbodies in Land Converted to Flooded Land

Other Constructed Waterbody	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	14,846	1015	590	542	442	393	354

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-20: Surface Area (ha) of Other Constructed Waterbodies in Land Converted to Flooded Land

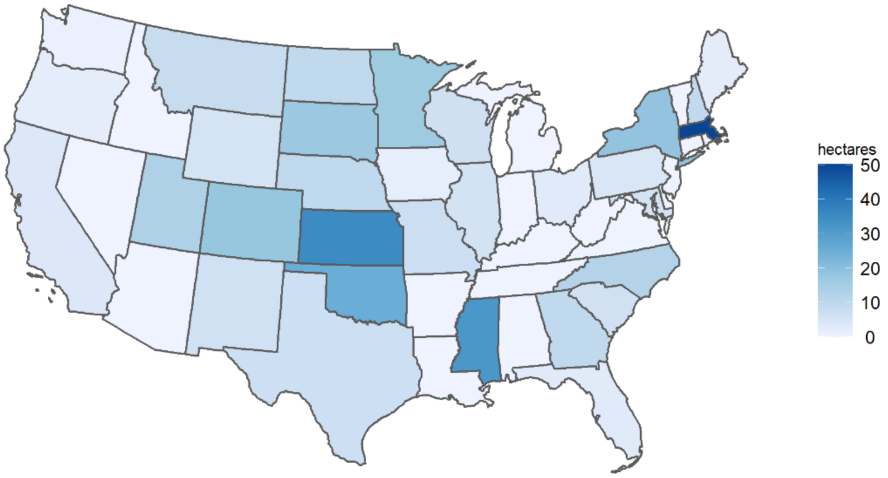

Table 6-107: State Surface Area (ha) Totals of Other Constructed Waterbodies in Land Converted to Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	240	11	3	3	0	0	0
Arizona	29	5	5	5	0	0	0
Arkansas	255	0	0	0	0	0	0
California	98	16	5	5	5	4	4
Colorado	140	27	27	27	18	18	18
Connecticut	46	0	0	0	0	0	0
Delaware	7	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0

Florida	46	16	6	6	6	3	3
Georgia	611	17	9	9	9	9	9
Idaho	44	0	0	0	0	0	0
Illinois	333	38	12	11	6	6	6
Indiana	81	7	0	0	0	0	0
Iowa	1,062	33	13	13	13	9	2
Kansas	1,636	74	65	58	42	35	35
Kentucky	184	2	2	0	0	0	0
Louisiana	95	5	0	0	0	0	0
Maine	23	4	2	2	2	2	2
Maryland	38	6	6	6	6	6	6
Massachusetts	70	65	72	67	61	57	50
Michigan	99	13	2	0	0	0	0
Minnesota	96	25	30	30	30	30	16
Mississippi	421	70	59	44	44	39	32
Missouri	2,375	23	7	7	7	7	7
Montana	298	5	13	13	13	8	8
Nebraska	751	44	35	35	9	9	9
Nevada	7	20	2	0	0	0	0
New Hampshire	62	20	9	9	9	9	9
New Jersey	15	3	3	3	0	0	0
New Mexico	9	0	6	6	6	6	6
New York	193	70	19	19	19	19	19
North Carolina	225	41	14	14	14	14	12
North Dakota	66	41	17	17	9	9	9
Ohio	202	38	13	3	3	3	3
Oklahoma	1,012	52	35	35	32	25	25
Oregon	81	18	5	5	2	2	2
Pennsylvania	137	20	5	5	5	5	5
Rhode Island	1	0	0	0	0	0	0
South Carolina	462	26	11	9	9	9	6
South Dakota	112	48	28	26	26	17	17
Tennessee	198	16	9	9	2	0	0
Texas	2,428	45	17	12	8	7	7
Utah	45	0	8	13	13	13	13
Vermont	61	4	0	0	0	0	0
Virginia	171	0	0	0	0	0	0
Washington	98	33	3	3	1	1	1
West Virginia	0	0	0	0	0	0	0
Wisconsin	154	11	7	7	7	7	7
Wyoming	28	3	5	5	5	5	5
TOTAL	**14,846**	**1,015**	**590**	**542**	**442**	**393**	**354**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Uncertainty

Uncertainty in estimates of CO_2 and CH_4 emissions from Land Converted to Flooded Land–*Other Constructed Water Bodies* include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in the NHD, NID, and NW are unknown, but uncertainty for remote sensing products is ±10 to 15 percent (IPCC 2003). EPA assumes an uncertainty of ±15 percent for the flooded land area inventory based on expert judgment. These uncertainties do not include the underestimate of pond surface area discussed above.

Table 6-108: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(kt CO_2 Eq.)	(kt CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Freshwater ponds	CH_4	2	2	2	-4.5%	5.0%
Freshwater ponds	CO_2	2	2	2	-4.1%	3.6%
Total		**3**	**3**	**4**	**-3.6%**	**4.1%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS with collaboration from many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[103] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics' (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

The distribution of U.S. waterbodies less than 8 ha is well known, but the presence or absence of water level control structures associated with these small waterbodies is not well documented in national data sources. To improve the representation of managed ponds in future inventories, EPA will attempt to locate state or county records on small dam construction permits and/or inspection records to supplement records in the NID. EPA will also use surrounding land use as a proxy for management. For example, a pond surrounded by cultivated land is likely subject to water level management and should be included in the inventory. Even if the pond were not subject to water level management, greenhouse gas emissions from the system are likely enhanced by elevated nutrient and sediment inputs from the surrounding managed lands, thus the emissions should be considered anthropogenic and included in the inventory.

Hawaii, Alaska, and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[104] an enhanced version of the NHD used in this Inventory.

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[103] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[104] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

6.10 Settlements Remaining Settlements (CRF Category 4E1)

Soil Carbon Stock Changes (CRF Category 4E1)

Soil organic C stock changes for *Settlements Remaining Settlements* occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in *Settlements Remaining Settlements*. This approach is consistent with the assumption of the Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in *Settlements Remaining Settlements*.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[105] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements Remaining Settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2015 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2018)[106] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The Inventory includes settlements on privately-owned lands in the conterminous United States and Hawaii. Alaska and the small amount of settlements on federal lands are not included in this Inventory even though these areas are part of the U.S. managed land base. This leads to a discrepancy with the total amount of managed area in *Settlements Remaining Settlements* (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future Inventory.

CO_2 emissions from drained organic soils in settlements are 15.9 MMT CO_2 Eq. (4.3 MMT C) in 2020 (See Table 6-109 and Table 6-110). Although the flux is relatively small, the amount has increased by over 40 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-109: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT CO_2 Eq.)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Organic Soils	11.3		12.2		16.0	16.0	15.9	15.9	15.9

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[105] N_2O emissions from soils are included in the N_2O Emissions from Settlement Soils section.

[106] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Settlements Remaining Settlements* in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-110: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT C)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Organic Soils	3.1		3.3		4.4	4.4	4.3	4.3	4.3

Methodology and Time-Series Consistency

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in *Settlements Remaining Settlements* (IPCC 2006). Organic soils in *Settlements Remaining Settlements* are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2018 NRI (USDA-NRCS 2018) with additional information from the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). It is assumed that all settlement area on organic soils is drained, and those areas are provided in Table 6-111 (See Section 6.1, Representation of the U.S. Land Base for more information). The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-111). The area of land on organic soils in *Settlements Remaining Settlements* has increased from 220 thousand hectares in 1990 to over 303 thousand hectares in 2015. The area of land on organic soils are not currently available from NRI for *Settlements Remaining Settlements* after 2015.

Table 6-111: Thousands of Hectares of Drained Organic Soils in *Settlements Remaining Settlements*

Year	Area (Thousand Hectares)
1990	220
2005	235
2014	291
2015	303
2016	ND
2017	ND
2018	ND
2019	ND
2020	ND

Note: No NRI data are available after 2015, designated as ND (No data).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2015, the total area of organic soils in *Settlements Remaining Settlements* is multiplied by the country-specific emission factors for *Cropland Remaining Cropland* under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 in Cropland Remaining Cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied in future Inventories to recalculate the estimates beyond 2015 as activity data become available.

Uncertainty

Uncertainty for the Tier 2 approach is derived using a Monte Carlo approach, along with additional uncertainty propagated through the Monte Carlo Analysis for 2016 to 2020 based on the linear time series model. The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 6-112. Soil C losses from drained organic soils in *Settlements Remaining Settlements* for 2020 are estimated to be between 7.4 and 24.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 53 percent below and 53 percent above the 2020 emission estimate of 15.9 MMT CO_2 Eq.

Table 6-112: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.9	7.4	24.4	-53%	53%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

There were no recalculations to the 1990 through 2019 time series in this Inventory.

Planned Improvements

This source will be updated to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. See Table 6-113 for the amount of managed land area in *Settlements Remaining Settlements* that is not included in the Inventory due to these omissions. The managed settlements area that is not included in the Inventory is in the range of 150 to 160 thousand hectares each year. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-113: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	SRS Managed Land Area (Section 6.1)	SRS Area Included in Inventory	SRS Area Not Included in Inventory
1990	30,585	30,425	159
1991	30,589	30,430	159
1992	30,593	30,434	159
1993	30,505	30,346	159
1994	30,423	30,264	159
1995	30,365	30,206	159
1996	30,316	30,157	158
1997	30,264	30,105	158
1998	30,200	30,041	159

1999	30,144	29,992	152
2000	30,101	29,949	152
2001	30,041	29,889	152
2002	30,034	29,882	152
2003	30,530	30,378	152
2004	31,011	30,859	152
2005	31,522	31,370	152
2006	31,964	31,812	152
2007	32,469	32,317	152
2008	33,074	32,922	152
2009	33,646	33,494	152
2010	34,221	34,069	152
2011	34,814	34,662	152
2012	35,367	35,215	152
2013	36,308	36,156	152
2014	37,281	37,129	152
2015	38,210	38,058	152
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Changes in Carbon Stocks in Settlement Trees (CRF Source Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 116.3 MMT CO_2 Eq. (31.7 MMT C) over the period from 1990 through 2020. Net C sequestration from settlement trees in 2020 is estimated to be 129.8 MMT CO_2 Eq. (35.4 MMT C) (Table 6-114). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses vs tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base C flux estimates. Annual sequestration increased by 35 percent between 1990 and 2020 due to increases in settlement area and changes in tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas are less than in forests and this tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the C stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for *Forest Lands).*

Table 6-114: Net Flux from Trees in *Settlements Remaining Settlements* (MMT CO_2 Eq. and MMT C)[a]

Year	MMT CO_2 Eq.	MMT C
1990	(96.4)	(26.3)
2005	(117.4)	(32.0)

2016	(129.8)	(35.4)
2017	(129.8)	(35.4)
2018	(129.8)	(35.4)
2019	(129.8)	(35.4)
2020	(129.8)	(35.4)

[a] These estimates include net CO_2 and C flux from trees on *Settlements Remaining Settlements* and Land Converted to Settlements as it is not possible to report on these separately at this time.

Note: Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlements area is defined in Section 6.1 Representation of the U.S. Land Base as a land-use category representing developed areas. The data used to estimate settlement area within Section 6.1 comes from the NRI as updated through 2015 with the extension of the time series through 2018 based on assuming the settlements area is the same as 2015, while harmonizing these data with the FIA dataset, which are available through 2018, and the NLCD dataset, which is available through 2016. Settlement areas for 2020 are held constant with the 2018 values. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of CO_2 flux (Table 6-114) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. NLCD developed classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) "Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes." Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as Developed Open Space.

b) "Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units." Plots designated as single family or low-density residential land were classified as Developed, Low Intensity.

c) “Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units.” Plots designated as medium density residential, other urban or mixed urban were classified as Developed, Medium Intensity.

d) “Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover.” Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as Developed, High Intensity.

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2011 and 2016 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2020: used 2011 NLCD tree cover adjusted with 2016 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net C sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate C in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross C sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration estimates to obtain estimates of net C sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[107] and Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-115). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service’s i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total C stored and annual C sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to C by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement

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[107] See http://www.itreetools.org.

trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. Estimated C storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-115: Carbon Storage (kg C/m² tree cover), Gross and Net Sequestration (kg C/m² tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

			Sequestration						
City	Storage	SE	Gross	SE	Net	SE	Ratio[a]	Tree Cover	SE
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7
Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7
San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4

South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE (Standard Error)
NA (Not Available)
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration – that is, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each tree were then scaled up to city estimates using tree population information. Total C sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross C sequestration accounts for all C sequestered, net C sequestration for settlement trees considers C emissions associated with tree death and removals. The third step in the methodology estimates net C emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross C emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-116) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual C sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-116). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual C sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Equation 6-1: Net State Annual Carbon Sequestration

Net state annual C sequestration (t C/yr) = Gross state sequestration rate (t C/ha/yr) × Net to Gross state sequestration ratio × state settlement Area (ha) × % state tree cover in settlement area

The results for all 50 states and the District of Columbia are given in Table 6-116. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net C sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-116: Estimated Annual C Sequestration (Metric Tons C/Year), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2/ year) for settlement areas in United States by State and the District of Columbia (2020)

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	2,060,001	1,501,070	53.5	0.376	0.274	0.73
Alaska	111,722	81,409	47.4	0.169	0.123	0.73
Arizona	172,750	125,878	4.6	0.388	0.283	0.73
Arkansas	1,266,164	922,622	48.9	0.362	0.264	0.73
California	2,007,869	1,463,083	16.9	0.426	0.311	0.73
Colorado	142,719	103,996	8.0	0.216	0.157	0.73
Connecticut	618,683	450,818	58.7	0.262	0.191	0.73
Delaware	97,533	71,070	24.4	0.366	0.267	0.73
DC	11,995	8,741	25.1	0.366	0.267	0.73
Florida	4,322,610	3,149,776	40.3	0.520	0.379	0.73
Georgia	3,411,478	2,485,857	56.3	0.387	0.282	0.73
Hawaii	285,700	208,182	41.7	0.637	0.464	0.73
Idaho	59,611	43,437	7.4	0.201	0.146	0.73
Illinois	662,891	483,032	15.5	0.310	0.226	0.73
Indiana	472,905	437,275	17.1	0.274	0.254	0.92
Iowa	177,692	129,480	8.6	0.263	0.191	0.73
Kansas	290,461	226,027	10.8	0.310	0.241	0.78
Kentucky	926,269	674,949	36.8	0.313	0.228	0.73
Louisiana	1,512,145	1,101,861	47.0	0.435	0.317	0.73
Maine	394,471	287,441	55.5	0.242	0.176	0.73
Maryland	818,044	596,088	40.1	0.353	0.257	0.73
Massachusetts	1,002,723	730,659	57.2	0.278	0.203	0.73
Michigan	1,343,325	978,847	34.7	0.241	0.175	0.73
Minnesota	313,364	228,340	13.1	0.251	0.183	0.73
Mississippi	1,518,448	1,106,454	57.3	0.377	0.275	0.73
Missouri	850,492	619,732	23.2	0.313	0.228	0.73
Montana	48,911	35,640	4.9	0.201	0.147	0.73
Nebraska	98,584	83,192	7.3	0.261	0.220	0.84

Nevada	41,181	30,008	4.8	0.226	0.165	0.73
New Hampshire	363,989	265,229	59.3	0.238	0.174	0.73
New Jersey	904,868	659,355	40.7	0.321	0.234	0.73
New Mexico	177,561	129,384	10.2	0.288	0.210	0.73
New York	1,531,415	1,115,903	39.9	0.263	0.192	0.73
North Carolina	3,064,797	2,233,239	54.1	0.341	0.249	0.73
North Dakota	18,492	8,787	1.8	0.244	0.116	0.48
Ohio	1,248,841	909,999	28.2	0.271	0.198	0.73
Oklahoma	699,044	509,376	22.1	0.364	0.265	0.73
Oregon	682,468	497,297	39.9	0.265	0.193	0.73
Pennsylvania	1,794,939	1,307,927	40.2	0.267	0.195	0.73
Rhode Island	121,940	88,855	50.0	0.283	0.206	0.73
South Carolina	1,801,029	1,312,364	53.8	0.370	0.269	0.73
South Dakota	29,489	25,573	2.9	0.258	0.224	0.87
Tennessee	1,591,278	1,422,789	41.1	0.332	0.297	0.89
Texas	4,239,494	3,089,211	28.5	0.403	0.294	0.73
Utah	118,880	86,625	11.7	0.235	0.172	0.73
Vermont	176,564	128,658	50.6	0.234	0.170	0.73
Virginia	1,968,537	1,434,422	52.9	0.321	0.234	0.73
Washington	1,063,871	775,216	37.6	0.282	0.206	0.73
West Virginia	699,320	509,577	64.1	0.264	0.192	0.73
Wisconsin	697,863	508,515	25.9	0.246	0.180	0.73
Wyoming	29,984	21,849	4.7	0.199	0.145	0.73
Total	**48,065,406**	**35,405,113**				

Uncertainty

Uncertainty associated with changes in C stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net C sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-117). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there is likely some overlap between the settlement tree C estimates and the forest tree C estimates (e.g., Nowak et al. 2013). Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2020. The results of this quantitative uncertainty analysis are summarized in Table 6-117. The change in C stocks in *Settlement Trees* in 2020 was estimated to be between -195.4 and -62.2 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2020 flux estimate of -129.8 MMT CO_2 Eq.

Table 6-117: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in C Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO_2	(129.8)	(195.42)	(62.22)	-51%	52%

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

There were no recalculations to the 1990 through 2019 time series in this Inventory.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1 Representation of the U.S. Land Base, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between *Settlement Trees* and the forest land categories. Estimates for *Settlement Trees* are based on tree cover in settlement areas. What needs to be determined is how much of this settlement area tree cover might also be accounted for in “forest” area assessments as some of these forests may fall within settlement areas. For example, “forest” as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the C reported in the Forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown. Future research may also enable more complete coverage of changes in the C stock of trees for all settlements land.

To provide more accurate emissions estimates in the future, the following actions will be taken:

a) Photo-interpret settlement tree cover in 2021 to update tree cover estimates and trends
b) Update photo-interpretation for settlement areas using 2016 NLCD developed land information
c) Develop spatially explicit and spatially continuous representations of land to eliminate the overlap between forest and settlement areas, as well as allow for improved estimates in “settlement areas."

N_2O Emissions from Settlement Soils (CRF Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N_2O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *Histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., ammonia [NH_3] and nitrogen oxide [NO_x] volatilization, nitrate [NO_3^-] leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in *Settlements Remaining Settlements*[108] are 2.5 MMT CO_2 Eq. (8 kt of N_2O) in 2020. There is an overall increase of 23 percent from 1990 to 2020 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-118.

Table 6-118: N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2016	2017	2018	2019	2020
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.6**	**2.5**	**1.9**	**2.0**	**2.0**	**2.1**	**2.1**
Synthetic Fertilizers	0.8	1.6	0.9	1.0	1.0	1.1	1.1
Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.6	0.7	0.8	0.8	0.8	0.8	0.8
Indirect N_2O Emissions from Soils	**0.4**	**0.6**	**0.3**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**2.0**	**3.1**	**2.2**	**2.3**	**2.4**	**2.4**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**6**	**9**	**6**	**7**	**7**	**7**	**7**
Synthetic Fertilizers	3	6	3	3	4	4	4
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	2	2	3	3	3	3	3
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**7**	**10**	**8**	**8**	**8**	**8**	**8**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.1—Wastewater Treatment and Discharge for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2020 are based on 2012 values adjusted for annual total N fertilizer sales in the United States because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. The total amount of fertilizer N

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[108] Estimates of Soil N_2O for *Settlements Remaining Settlements* include emissions from Land Converted to Settlements because it was not possible to separate the activity data.

applied to settlements is multiplied by the IPCC default emission factor (1 percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2012.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2020.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2015 NRI (USDA-NRCS 2018) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). To estimate annual emissions from 1990 to 2015, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). This Inventory does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future Inventory.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2015 for fertilizer and from 1990 to 2020 for biosolids.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 for biosolids. For synthetic fertilizer and drainage of organic soils, the methods described above are applied for 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 in *Cropland Remaining Cropland*). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The time series will be recalculated for the years beyond 2015 in a future Inventory with the methods described above for 1990 to 2015. This Inventory does incorporate updated activity data on biosolids application in settlements through 2020.

Uncertainty

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variation in the total amount of fertilizer N and biosolids application, which in turn, leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[109] Uncertainty in the area of drained organic soils is based on the estimated variance from the NRI survey (USDA-NRCS 2018). For 2016 to 2020, there is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods.

For biosolids, there is uncertainty in the amounts of biosolids applied to non-agricultural lands and used in surface disposal. These uncertainties are derived from variability in several factors, including: (1) N content of biosolids; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the biosolids disposal practice

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[109] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

distributions to non-agricultural land application and surface disposal. In addition, there is uncertainty in the direct and indirect emission factors that are provided by IPCC (2006).

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-119. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2020 are estimated to be between 1.3 and 2.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 38 percent below to 22 percent above the 2020 emission estimate of 2.1 MMT CO_2 Eq. Indirect N_2O emissions in 2020 are between 0.2 and 0.5 MMT CO_2 Eq., ranging from 38 percent below to 38 percent above the estimate of 0.4 MMT CO_2 Eq.

Table 6-119: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
Settlements Remaining Settlements			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Emissions from Soils	N_2O	2.1	1.3	2.5	-38%	22%
Indirect N_2O Emissions from Soils	N_2O	0.4	0.2	0.5	-38%	38%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: These estimates include direct and indirect N_2O emissions from *Settlements Remaining Settlements* and Land Converted to Settlements because it was not possible to separate the activity data.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked. An error was found in the uncertainty calculation that was corrected.

Recalculations Discussion

Recalculations are associated with updated estimates for 2019 using the linear extrapolation method. As a result, N_2O Emissions from Settlement Soils has a smaller emission of 0.04 MMT CO_2 Eq. in 2019. This represents less than 1 percent decrease in emissions compared to the previous Inventory.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amount and area of drained organic soils will be compiled to update emissions estimates from 2016 to 2020 in a future Inventory.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRF Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the Inventory are associated with particular land uses. For example, harvested wood products are reported under *Forest Land Remaining Forest Land* because these wood products originated from the forest ecosystem. Similarly, C stock changes in yard trimmings and food scraps are reported under *Settlements Remaining Settlements* because the bulk of the C, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this Inventory they are reported with the yard trimmings in the *Settlements Remaining Settlements* section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1 Representation of the U.S. Land Base), and reporting these C stock changes that occur entirely within landfills fits most appropriately within the *Settlements Remaining Settlements* section.

Both the estimated amount of yard trimmings collected annually and the fraction that is landfilled have been declining. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2020). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent estimated 1.1 percent increase between 1990 and 2020 in the tonnage of yard trimmings generated (i.e., collected for composting or disposal in landfills) per year. At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills per year—from 72 percent in 1990 to 30 percent in 2020. The net effect of the slight increase in generation and the increase in composting is a 58 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by an estimated 165 percent since 1990, and while the proportion of total food scraps generated that are eventually discarded in landfills has decreased, from an estimated 82 percent in 1990 to 55 percent in 2020, the tonnage disposed of in landfills has increased considerably (by an estimated 78 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2020, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual carbon stock *net changes* from food scraps have generally decreased as well (as shown in Table 6-120 and Table 6-121). As described in the Methodology section, the carbon stocks are modeled using data on the amount of food scraps landfilled since 1960. These food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable “older” carbon stock, thus resulting in less annual change in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual *net change* landfill C storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 12.2 MMT CO_2 Eq. (3.3 MMT C) in 2020 (Table 6-120 and Table 6-121), a decrease of 50 percent over the time series.

Table 6-120: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990		2005		2016	2017	2018	2019	2020
Yard Trimmings	**(20.1)**		**(7.5)**		**(6.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.1)**
Grass	(1.7)		(0.6)		(0.5)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)		(3.4)		(3.0)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)		(3.4)		(2.8)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**		**(3.9)**		**(3.7)**	**(5.6)**	**(5.2)**	**(4.8)**	**(4.1)**
Total Net Flux	**(24.5)**		**(11.4)**		**(10.0)**	**(13.8)**	**(13.4)**	**(13.1)**	**(12.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-121: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Yard Trimmings	**(5.5)**	**(2.0)**	**(1.7)**	**(2.3)**	**(2.3)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(0.8)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(0.8)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.0)**	**(1.5)**	**(1.4)**	**(1.3)**	**(1.1)**
Total Net Flux	**(6.7)**	**(3.1)**	**(2.7)**	**(3.8)**	**(3.7)**	**(3.6)**	**(3.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years and are based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled C stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings;

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The C storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable C.

The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2017 and 2018. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, 2015, and 2017 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2019 and 2020 were unavailable, landfilled material generation, recovery, and disposal data for 2019 and 2020 were proxied equal to 2018 values.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-122).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of the initial C (shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-122).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are reported in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-122.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

Similar to the methodology in the Landfills section of the Inventory (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 $year^{-1}$, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 $year^{-1}$), but not for the other two overall MSW decay rates.

To maintain consistency between landfill methodologies across the Inventory, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 $year^{-1}$ through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. Precipitation range percentages weighted by population are updated over time as new Census data are available, to remain consistent with percentages used in Section 7.1. The component-specific decay rates are shown in Table 6-122.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total C Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated (year),
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$ = Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),
n = Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i = Moisture content of waste *i* (percent of water),
CS_i = Proportion of initial C that is stored for waste *i* (percent),
ICC_i = Initial C content of waste *i* (percent),
e = Natural logarithm, and
k = First-order decay rate for waste *i*, (year^{-1}).

For a given year *t*, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year *t* is calculated in as the change in C stock compared to the preceding year according to Equation 6-3:

Equation 6-3: C Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 1, the C placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2020, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2020), the total landfill C from food scraps in 2020 was 49.6 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2019, yielding a value of 285.7 million metric tons (as shown in Table 6-123). In the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-121) is the difference in the landfill C stock for the following year (2021 C stock was forecast using 1990 to 2020 C stocks) and the stock in the current year. For example, the net change in 2020 shown in Table 6-121 (2.9 MMT C) is equal to the stock in 2021 (288.7 MMT C) minus the stock in 2020 (285.7 MMT C). The C stocks calculated through this procedure are shown in Table 6-123.

Table 6-122: Moisture Contents, C Storage Factors (Proportions of Initial C Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate (year^{-1})	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-123: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020	2021[a]
Yard Trimmings	**156.0**	**203.1**	**227.7**	**229.4**	**231.6**	**233.9**	**236.1**	**238.3**
Branches	14.6	18.1	20.3	20.5	20.7	20.9	21.1	21.3
Leaves	66.7	87.4	98.6	99.4	100.4	101.5	102.5	103.5
Grass	74.7	97.7	108.7	109.5	110.5	111.5	112.5	113.5
Food Scraps	**17.9**	**33.2**	**44.4**	**45.4**	**46.9**	**48.3**	**49.6**	**50.7**
Total Carbon Stocks	**173.9**	**236.3**	**272.0**	**274.8**	**278.5**	**282.2**	**285.7**	**289.1**

[a] 2021 C stock estimate was forecasted using 1990 to 2020 data.

Note: Totals may not sum due to independent rounding.

To develop the 2021 C stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2021, based on data from 1990 through 2020. These forecasted values were used to calculate net changes in carbon stocks for 2020. Excel's FORECAST.ETS function was used to predict a 2021 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2021.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. The same data source was used for the analysis, when available. When data were unavailable, missing values were estimated using linear interpolation or forecasting, as noted above.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2020. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-124. Total yard trimmings and food scraps CO_2 flux in 2020 was estimated to be between -20.5 and -5.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68 percent below to 56 percent above the 2020 flux estimate of -12.2 MMT CO_2 Eq.

Table 6-124: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Yard Trimmings and Food Scraps	CO_2	(12.2)	(20.5)	(5.4)	-68%	56%

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for *Landfilled Yard Trimmings and Food Scraps* included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The current Inventory has been revised to reflect updated data from the most recent *Advancing Sustainable Materials Management: Facts and Figures* report. Recalculations based on these updates resulted in 2.8 percent change in the annual carbon stocks and sequestration values as compared to the previous inventory values. The largest changes occurred in the most recent years: a 3 percent increase in sequestration in 2016, a 40.3 percent increase in sequestration in 2017, a 37.5 percent increase in sequestration in 2018, and a 28.6 percent increase in sequestration in 2019. Large changes in yard trimmings can be attributed to updates to 2017 and 2018 yard trimmings and food scraps landfilled values reported in *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020). A large increase in sequestration in 2019 can be attributed to updated generation values as well – 2019 landfill data were unavailable and were reported as 2018 values.

The bulk of the increase in sequestration is attributed to a change in food scrap measurement methodology in the *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020). The revised methodology more fully captures flows of recovery of excess food and food waste for 2018 data. The 2018 food scraps recovery estimates include nine management pathways, three of which previously existed in the report (composting, combustion with energy recovery, and landfilling). The six new management pathways are:

- Animal feed
- Bio-based materials/biochemical processing
- Land application
- Donation
- Codigestion/anaerobic digestion
- Sewer/wastewater treatment

Food scrap generation estimates increased over 50 percent between 2017 and 2018, from 40.7 million tons to 63.1 million tons, due to the change in food generation measurement. Food scrap recovery estimates increased by nearly 800 percent (from 2,570 thousand tons in 2017 to 20,300 tons in 2018). Data on the six management pathways from 1990 to 2017 were not available.

Planned Improvements

EPA plans to evaluated data from recent peer-reviewed literature that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values.

EPA also plans to investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches, as well as evaluate using decay rates that vary over time based on Census data changes over time. Currently the inventory calculations use 2010 U.S. Census data.

Other improvements include investigation into yard waste composition to determine if changes need to be made based on changes in residential practices, a review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with Inventory estimates.

Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to apply data for the remaining time series.

Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in Inventory estimates, such as debris from road construction and commercial food waste not included in other chapter estimates.

6.11 Land Converted to Settlements (CRF Category 4E2)

Land Converted to Settlements includes all settlements in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[110] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils on settlements in federal lands are also not included in this Inventory. Consequently, there is a discrepancy between the total amount of managed area for Land Converted to Settlements (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis.

Land use change can lead to large losses of carbon (C) to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for Land Converted to Settlements, but there is limited reporting of other pools in this Inventory. Loss of aboveground and belowground biomass, dead wood and litter C are reported for Forest Land Converted to Settlements, but not for other land use conversions to settlements.

Forest Land Converted to Settlements is the largest source of emissions from 1990 to 2020, accounting for approximately 75 percent of the average total loss of C among all of the land use conversions in Land Converted to Settlements. Losses of aboveground and belowground biomass, dead wood and litter C losses in 2020 are 36.7, 7.0, 6.4, and 9.3 MMT CO_2 Eq., respectively (10.0, 1.9, 1.7, and 2.5 MMT C). Mineral and organic soils also lost 16.2 and 2.4 MMT CO_2 Eq. in 2020 (4.4 and 0.6 MMT C). The total net flux is 77.9 MMT CO_2 Eq. in 2020 (21.2 MMT C), which is a 28 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-125 and Table 6-126). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter C.

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[110] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of Land Converted to Settlements in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

Table 6-125: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Settlements	**3.4**	**9.8**	**6.0**	**6.0**	**5.9**	**5.9**	**5.9**
Mineral Soils	2.8	8.4	5.2	5.2	5.2	5.1	5.1
Organic Soils	0.6	1.3	0.8	0.8	0.8	0.8	0.8
Forest Land Converted to Settlements	**52.6**	**57.7**	**61.3**	**61.5**	**61.6**	**61.6**	**61.5**
Aboveground Live Biomass	31.7	34.2	36.5	36.6	36.7	36.7	36.7
Belowground Live Biomass	6.1	6.5	7.0	7.0	7.0	7.0	7.0
Dead Wood	5.5	5.9	6.4	6.4	6.4	6.4	6.4
Litter	8.0	8.7	9.3	9.3	9.3	9.3	9.3
Mineral Soils	1.1	2.0	1.9	1.9	1.9	1.9	1.9
Organic Soils	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Grassland Converted to Settlements	**5.2**	**16.3**	**11.3**	**11.3**	**11.3**	**11.3**	**11.2**
Mineral Soils	4.6	14.9	10.4	10.4	10.4	10.4	10.3
Organic Soils	0.6	1.4	0.9	0.9	0.9	0.9	0.9
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**
Mineral Soils	(0.4)	(1.6)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Organic Soils	+	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Converted to Settlements	**+**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
Mineral Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	+	0.4	0.3	0.3	0.3	0.3	0.3
Total Aboveground Biomass Flux	**31.7**	**34.2**	**36.5**	**36.6**	**36.7**	**36.7**	**36.7**
Total Belowground Biomass Flux	**6.1**	**6.5**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**
Total Dead Wood Flux	**5.5**	**5.9**	**6.4**	**6.4**	**6.4**	**6.4**	**6.4**
Total Litter Flux	**8.0**	**8.7**	**9.3**	**9.3**	**9.3**	**9.3**	**9.3**
Total Mineral Soil Flux	**8.1**	**23.8**	**16.3**	**16.2**	**16.2**	**16.2**	**16.2**
Total Organic Soil Flux	**1.4**	**3.6**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**
Total Net Flux	**60.8**	**82.8**	**77.8**	**77.9**	**78.0**	**77.9**	**77.9**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-126: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Settlements	**0.9**	**2.7**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**
Mineral Soils	0.8	2.3	1.4	1.4	1.4	1.4	1.4
Organic Soils	0.2	0.4	0.2	0.2	0.2	0.2	0.2
Forest Land Converted to Settlements	**14.3**	**15.7**	**16.7**	**16.8**	**16.8**	**16.8**	**16.8**
Aboveground Live Biomass	8.6	9.3	10.0	10.0	10.0	10.0	10.0
Belowground Live Biomass	1.7	1.8	1.9	1.9	1.9	1.9	1.9
Dead Wood	1.5	1.6	1.7	1.7	1.7	1.7	1.7
Litter	2.2	2.4	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.4**	**4.4**	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**
Mineral Soils	1.3	4.1	2.8	2.8	2.8	2.8	2.8
Organic Soils	0.2	0.4	0.2	0.2	0.2	0.2	0.2

Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.1)	(0.4)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Aboveground Biomass Flux	**8.6**	**9.3**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
Total Belowground Biomass Flux	**1.7**	**1.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**
Total Dead Wood Flux	**1.5**	**1.6**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Litter Flux	**2.2**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**2.2**	**6.5**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
Total Organic Soil Flux	**0.4**	**1.0**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**
Total Net Flux	**16.6**	**22.6**	**21.2**	**21.3**	**21.3**	**21.3**	**21.2**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for Land Converted to Settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to settlements, as well as (2) the impact from all land use conversions to settlements on soil organic C stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for *Forest* Land Converted to Settlements. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020), however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks on these converted lands were assumed to be zero. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory, which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

This inventory also includes estimates of change in dead organic matter for standing dead, deadwood and litter. If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for Land Converted to Settlements according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018).

NRI survey locations are classified as Land Converted to Settlements in a given year between 1990 and 2015 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of Land Converted to Settlements in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate C stock changes for Land Converted to Settlements on mineral soils from 1990 to 2015. Data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific C stock change factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2015 NRI survey data (USDA-NRCS 2018) do not provide the information needed to assign different land use subcategories to settlements, such as turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic C with conversion to settlements under the assumption that there are additional soil organic C losses with land clearing, excavation and other activities associated with development. More specific factor values can be derived in future Inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic C stock changes from 2016 to 2020 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2016 to 2020 emissions in a future Inventory.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in Land Converted to Settlements are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing C at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2

emissions from 1990 to 2015, the area of organic soils in Land Converted to Settlements is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (See Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for C losses with *Forest* Land Converted to Settlements is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13. The uncertainty analysis for mineral soil organic C stock changes and annual C emission estimates from drained organic soils in Land Converted to Settlements is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-127 for each subsource (i.e., biomass C, dead wood, litter, soil organic C in mineral soil and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., as described in the previous paragraph. There are also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic C stock changes from 2016 to 2020. The combined uncertainty for total C stocks in Land Converted to Settlements ranges from 34 percent below to 34 percent above the 2020 stock change estimate of 77.9 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**5.9**	**2.1**	**9.8**	**-65%**	**65%**
Mineral Soil C Stocks	5.1	1.3	8.9	-74%	74%
Organic Soil C Stocks	0.8	0.1	1.5	-86%	86%
Forest Land Converted to Settlements	**61.5**	**37.3**	**85.8**	**-39%**	**39%**
Aboveground Biomass C Stocks	36.7	13.9	59.5	-62%	62%
Belowground Biomass C Stocks	7.0	2.6	11.4	-62%	62%
Dead Wood	6.4	2.4	10.3	-62%	62%
Litter	9.3	3.5	15.1	-62%	62%
Mineral Soil C Stocks	1.9	1.3	2.5	-32%	32%
Organic Soil C Stocks	0.3	0.1	0.5	-72%	72%
Grassland Converted to Settlements	**11.2**	**6.1**	**16.4**	**-46%**	**46%**
Mineral Soil C Stocks	10.3	5.2	15.4	-49%	49%
Organic Soil C Stocks	0.9	0.1	1.7	-90%	90%
Other Lands Converted to Settlements	**(1.2)**	**(2.0)**	**(0.4)**	**-68%**	**68%**
Mineral Soil C Stocks	(1.3)	(2.0)	(0.5)	-61%	61%
Organic Soil C Stocks	0.1	(0.1)	0.3	-168%	168%
Wetlands Converted to Settlements	**0.3**	**(0.2)**	**0.9**	**-150%**	**150%**
Mineral Soil C Stocks	0.1	+	0.1	-103%	103%
Organic Soil C Stocks	0.3	(0.2)	0.8	-182%	182%

Total: Land Converted to Settlements	**77.9**	**51.4**	**104.4**	**-34%**	**34%**
Aboveground Biomass C Stocks	**36.7**	**13.9**	**59.5**	**-62%**	**62%**
Belowground Biomass C Stocks	**7.0**	**2.6**	**11.4**	**-62%**	**62%**
Dead Wood	**6.4**	**2.4**	**10.3**	**-62%**	**62%**
Litter	**9.3**	**3.5**	**15.1**	**-62%**	**62%**
Mineral Soil C Stocks	**16.2**	**9.7**	**22.6**	**-40%**	**40%**
Organic Soil C Stocks	**2.4**	**(6.2)**	**10.9**	**-361%**	**361%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in *Forest* Land Converted to Settlements*,* and updated estimates for mineral and organic soils from 2016 to 2020 using the linear extrapolation method. As a result, Land Converted to Settlements has an estimated smaller C loss of 2.0 MMT CO_2 Eq. on average over the time series. This represents a 2.6 percent decrease in C stock changes for Land Converted to Settlements compared to the previous Inventory.

Planned Improvements

A planned improvement for the Land Converted to Settlements category is to develop an inventory of mineral soil organic C stock changes in Alaska and losses of C from drained organic soils in federal lands. This includes C stock changes for biomass, dead organic matter and soils. See Table 6-128 for the amount of managed land area in Land Converted to Settlements that is not included in the Inventory due to these omissions. The managed area that is not included in the Inventory ranges between 0 and about 600 thousand hectares depending on the year.

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the Inventory to included C losses associated with drained organic soils in settlements occurring on federal lands.

New land representation data will also be compiled, and the emissions data will be recalculated for the latter years in the time series that are estimated using data splicing methods in this Inventory. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-128: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	LCS Managed Land Area (Section 6.1)	LCS Area Included in Inventory	LCS Area Not Included in Inventory
1990	2,861	2,861	0
1991	3,238	3,238	0
1992	3,592	3,592	0
1993	4,178	4,107	72
1994	4,777	4,630	147
1995	5,384	5,161	223
1996	5,927	5,658	269
1997	6,520	6,174	346
1998	7,065	6,650	416
1999	7,577	7,116	461
2000	8,095	7,568	528
2001	8,544	7,947	597
2002	8,886	8,284	602
2003	8,941	8,335	606
2004	8,957	8,345	612
2005	8,947	8,341	606
2006	8,959	8,352	607
2007	8,902	8,295	607
2008	8,722	8,111	610
2009	8,541	7,930	611
2010	8,335	7,725	611
2011	8,108	7,498	611
2012	7,918	7,298	620
2013	7,504	6,932	572
2014	7,087	6,586	501
2015	6,589	6,165	424
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.12 Other Land Remaining Other Land (CRF Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of *Other Land Remaining Other Land* is known (see Table 6-4), research is ongoing to track C pools in this land use. Until such time that reliable and comprehensive estimates of C for *Other Land Remaining Other Land* can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on *Other Land Remaining Other Land* at this time.

6.13 Land Converted to Other Land (CRF Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-4), research is ongoing to track C across *Other Land Remaining Other Land* and *Land Converted to Other Land*. Until such time that reliable and comprehensive estimates of C across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on *Land Converted to Other Land* from fluxes on *Other Land Remaining Other Land* at this time.

7. Waste

Waste management and treatment activities are sources of greenhouse gas emissions (see Figure 7-1 and Figure 7-2). Landfills accounted for approximately 16.8 percent of total U.S. anthropogenic methane (CH_4) emissions in 2020, the third largest contribution of any CH_4 source in the United States. Additionally, wastewater treatment and discharge, composting of organic waste, and anaerobic digestion at biogas facilities accounted for approximately 2.8 percent, 0.4 percent, and less than 0.1 percent of U.S. CH_4 emissions, respectively. Nitrous oxide (N_2O) emissions resulted from the discharge of wastewater treatment effluents into aquatic environments were estimated, the wastewater treatment process itself, and composting. Together, these waste activities account for 6.0 percent of total U.S. N_2O emissions. Nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) are emitted by waste activities and are addressed separately at the end of this chapter. A summary of greenhouse gas emissions from the Waste chapter is presented in Table 7-1 and Table 7-2. Overall, in 2020, waste activities generated emissions of 155.6 MMT CO_2 Eq., or 2.6 percent of total U.S. greenhouse gas emissions.

Figure 7-1: 2020 Waste Sector Greenhouse Gas Sources

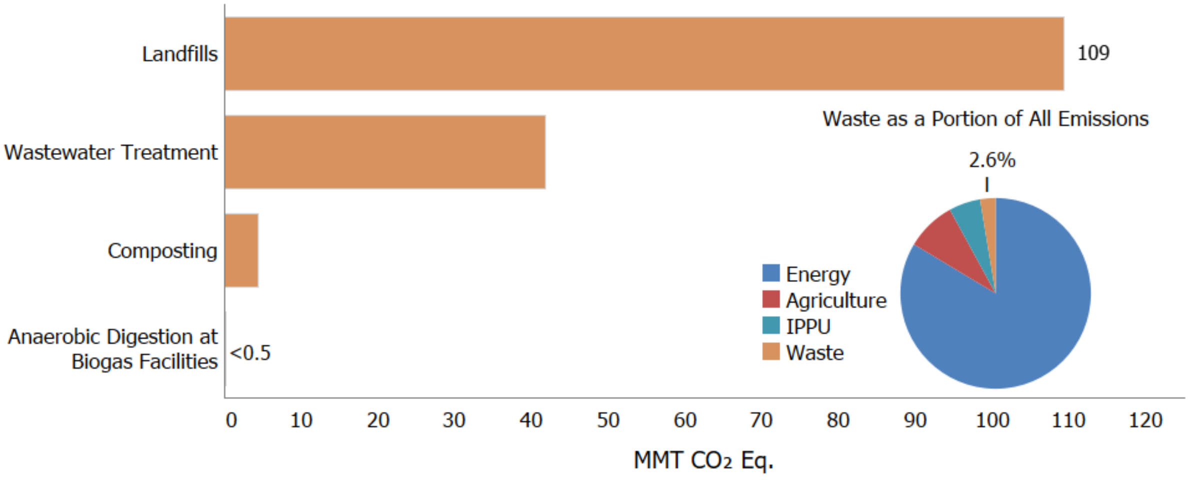

Figure 7-2: Trends in Waste Chapter Greenhouse Gas Sources

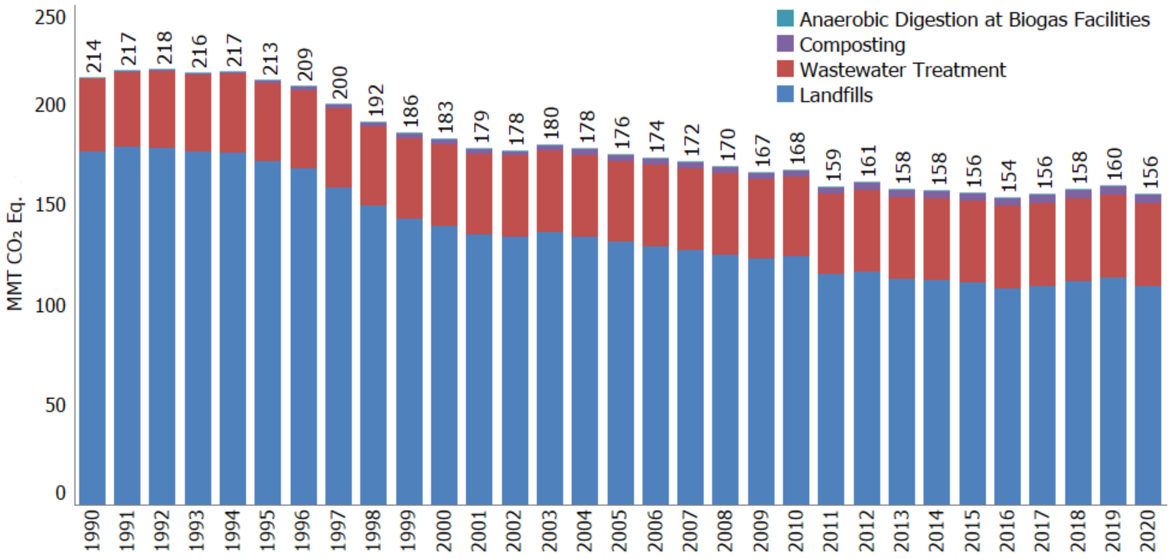

Table 7-1: Emissions from Waste (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CH_4	**197.3**	**153.6**	**129.1**	**130.3**	**132.4**	**134.1**	**130.0**
Landfills	176.6	131.5	107.9	109.2	111.7	113.6	109.3
Wastewater Treatment	20.3	20.1	18.7	18.5	18.3	18.1	18.3
Composting	0.4	1.9	2.3	2.5	2.3	2.3	2.3
Anaerobic Digestion at Biogas Facilities	+	+	0.2	0.2	0.2	0.2	0.2
N_2O	**16.9**	**22.0**	**24.8**	**25.4**	**25.5**	**25.4**	**25.6**
Wastewater Treatment	16.6	20.3	22.8	23.2	23.5	23.4	23.5
Composting	0.3	1.7	2.0	2.2	2.0	2.0	2.0
Total	**214.2**	**175.6**	**153.9**	**155.7**	**157.9**	**159.6**	**155.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 7-2: Emissions from Waste (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
CH_4	**7,890**	**6,144**	**5,164**	**5,212**	**5,296**	**5,365**	**5,201**
Landfills	7,063	5,262	4,318	4,368	4,467	4,545	4,373
Wastewater Treatment	812	806	748	740	732	723	730
Composting	15	75	91	98	90	91	91
Anaerobic Digestion at Biogas Facilities	1	2	7	6	6	6	6
N_2O	**57**	**74**	**83**	**85**	**86**	**85**	**86**
Wastewater Treatment	56	68	76	78	79	79	79
Composting	1	6	7	7	7	7	7

Note: Totals may not sum due to independent rounding.

Carbon dioxide (CO_2), CH_4, and N_2O emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2020 resulted in 13.5 MMT CO_2 Eq. emissions, more than half of which is attributable to the combustion of plastics. For more details on emissions from the incineration of waste, see Section 7.5. Greenhouse gas precursor emissions from the waste sector are presented in Section 7.6.

Each year, some emission and sink estimates in the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emission estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate. EPA revised the factor used to estimate non-consumed protein in domestic wastewater treatment. EPA also incorporated the Tier 2 methodology from *2019 Refinement* (IPCC 2019) for CH_4 emissions from the discharge of pulp and paper manufacturing wastewater to aquatic environments. EPA also revised the emissions factor for centralized aerobic systems and updated the BOD concentration for wastewater entering constructed wetlands as a tertiary treatment. Overall, these recalculations lead to an average decrease of 2.6 MMT CO_2 Eq. (1.5 percent) across the timeseries. For more information on specific methodological updates, please see the Recalculations Discussion for each category in this chapter.

Due to lack of data availability, EPA is not able to estimate emissions associated with sludge generated from the treatment of industrial wastewater or the amount of CH_4 flared at composting sites. Emissions reported in the Waste chapter for landfills, wastewater treatment, and anaerobic digestion at biogas facilities include those from all 50 states, including Hawaii and Alaska, the District of Columbia, and U.S. Territories. Emissions from landfills include modern, managed sites in most U.S. Territories except for outlying Pacific Islands. Emissions from domestic wastewater treatment include most U.S. Territories except for outlying Pacific Islands. Those emissions are likely insignificant as those outlying Pacific Islands (e.g., Baker Island) have no permanent population. No industrial wastewater treatment emissions are estimated for U.S. Territories, due to lack of data availability. However, industrial wastewater treatment emissions are not expected for outlying Pacific Islands and assumed to be small for other U.S. Territories. Emissions for composting include all 50 states, including Hawaii and Alaska, but not U.S. Territories. Composting emissions from U.S. Territories are assumed to be small. Similarly, EPA is not aware of any anerobic digestion at biogas facilities in U.S. Territories but will review this on an ongoing basis to include these emissions if they are occurring. See Annex 5 for more information on EPA's assessment of the sources not included in this Inventory.

Box 7-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals, including Relationship to Greenhouse Gas Reporting Data

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the emissions and removals presented in this report and this chapter are organized by source and sink categories and calculated using internationally-accepted methods provided by the Intergovernmental Panel on Climate Change (IPCC) in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines)* and its supplements and refinements. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common format in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement. The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and sinks provided in the Waste chapter do not preclude alternative examinations, but rather, this chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself, and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals from waste management and treatment activities.

EPA also collects greenhouse gas emissions data from individual facilities and suppliers of certain fossil fuels and industrial gases through its Greenhouse Gas Reporting Program (GHGRP). The GHGRP applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons and requires reporting by sources or suppliers in 41 industrial categories.

Annual reporting is at the facility level, except for certain suppliers of fossil fuels and industrial greenhouse gases. In general, the threshold for reporting is 25,000 metric tons or more of CO_2 Eq. per year. See Annex 9 "Use of EPA Greenhouse Gas Reporting Program in Inventory" for more information.

Waste Data from EPA's Greenhouse Gas Reporting Program

EPA uses annual GHGRP facility-level data in the Landfills category to compile the national estimate of emissions from municipal solid waste (MSW) landfills (see Section 7.1 of this chapter for more information). EPA uses directly reported GHGRP data for net CH_4 emissions from MSW landfills for the years 2010 to 2020 of the Inventory. MSW landfills subject to the GHGRP began collecting data in 2010. These data are also used to recalculate emissions from MSW landfills for the years 2005 to 2009 to ensure time-series consistency.

7.1 Landfills (CRF Source Category 5A1)

In the United States, solid waste is managed by landfilling, recovery through recycling or composting, and combustion through waste-to-energy facilities. Disposing of solid waste in modern, managed landfills is the most used waste management technique in the United States. More information on how solid waste data are collected and managed in the United States is provided in Box 7-3. The municipal solid waste (MSW) and industrial waste landfills referred to in this section are all modern landfills that must comply with a variety of regulations as discussed in Box 7-2. Disposing of waste in illegal dumping sites is not considered to have occurred in years later than 1980 and these sites are not considered to contribute to net emissions in this section for the timeframe of 1990 to the current Inventory year. MSW landfills, or sanitary landfills, are sites where MSW is managed to prevent or minimize health, safety, and environmental impacts. Waste is deposited in different cells and covered daily with soil; many have environmental monitoring systems to track performance, collect leachate, and collect landfill gas. Industrial waste landfills are constructed in a similar way as MSW landfills, but are used to dispose of industrial solid waste, such as RCRA Subtitle D wastes (e.g., non-hazardous industrial solid waste defined in Title 40 of the Code of Federal Regulations [CFR] in section 257.2), commercial solid wastes, or conditionally exempt small-quantity generator wastes (EPA 2016a).

After being placed in a landfill, organic waste (such as paper, food scraps, and yard trimmings) is initially decomposed by aerobic bacteria. After the oxygen has been depleted, the remaining waste is available for consumption by anaerobic bacteria, which break down organic matter into substances such as cellulose, amino acids, and sugars. These substances are further broken down through fermentation into gases and short-chain organic compounds that form the substrates for the growth of methanogenic bacteria. These methane (CH_4) producing anaerobic bacteria convert the fermentation products into stabilized organic materials and biogas consisting of approximately 50 percent biogenic carbon dioxide (CO_2) and 50 percent CH_4, by volume. Landfill biogas also contains trace amounts of non-methane organic compounds (NMOC) and volatile organic compounds (VOC) that either result from decomposition byproducts or volatilization of biodegradable wastes (EPA 2008).

Box 7-2: Description of a Modern, Managed Landfill in the United States

Modern, managed landfills are well-engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal, state, and tribal regulations. A modern, managed landfill is EPA's interpretation of the IPCC's terminology of a managed solid waste disposal site. Municipal solid waste (MSW) landfills must be designed to protect the environment from contaminants which may be present in the solid waste stream. Additionally, many new landfills collect and destroy landfill gas through flares or landfill gas-to-energy projects. Requirements for affected MSW landfills may include:

- Siting requirements to protect sensitive areas (e.g., airports, floodplains, wetlands, fault areas, seismic impact zones, and unstable areas);

- Design requirements for new landfills to ensure that Maximum Contaminant Levels (MCLs) will not be exceeded in the uppermost aquifer (e.g., composite liners and leachate collection systems);
- Leachate collection and removal systems;
- Operating practices (e.g., daily and intermediate cover, receipt of regulated hazardous wastes, use of landfill cover material, access options to prevent illegal dumping, use of a collection system to prevent stormwater run-on/run-off, record-keeping);
- Air monitoring requirements (explosive gases);
- Groundwater monitoring requirements;
- Closure and post-closure care requirements (e.g., final cover construction); and
- Corrective action provisions.

Specific federal regulations that affected MSW landfills must comply with include the 40 CFR Part 258 (Subtitle D of RCRA), or equivalent state regulations and the NSPS 40 CFR Part 60 Subpart WWW and XXX. [1] Additionally, state and tribal requirements may exist.

Methane and CO_2 are the primary constituents of landfill gas generation and emissions. Net carbon dioxide flux from carbon stock changes of materials of biogenic origin in landfills are estimated and reported under the Land Use, Land-Use Change, and Forestry (LULUCF) sector (see Chapter 6 of this Inventory). Nitrous oxide (N_2O) emissions from the disposal and application of sewage sludge on landfills are also not explicitly modeled as part of greenhouse gas emissions from landfills. Nitrous oxide emissions from sewage sludge applied to landfills as a daily cover or for disposal are expected to be relatively small because the microbial environment in an anaerobic landfill is not very conducive to the nitrification and denitrification processes that result in N_2O emissions. Furthermore, the *2006 IPCC Guidelines* did not include a methodology for estimating N_2O emissions from solid waste disposal sites “because they are not significant.” Therefore, only CH_4 generation and emissions are estimated for landfills under the Waste sector.

Methane generation and emissions from landfills are a function of several factors, including: (1) the total amount and composition of waste-in-place, which is the total waste landfilled annually over the operational lifetime of a landfill; (2) the characteristics of the landfill receiving waste (e.g., size, climate, cover material); (3) the amount of CH_4 that is recovered and either flared or used for energy purposes; and (4) the amount of CH_4 oxidized as the landfill gas – that is not collected by a gas collection system – passes through the cover material into the atmosphere. Each landfill has unique characteristics, but all managed landfills employ similar operating practices, including the application of a daily and intermediate cover material over the waste being disposed of in the landfill to prevent odor and reduce risks to public health. Based on recent literature, the specific type of cover material used can affect the rate of oxidation of landfill gas (RTI 2011). The most used cover materials are soil, clay, and sand. Some states also permit the use of green waste, tarps, waste derived materials, sewage sludge or biosolids, and contaminated soil as a daily cover. Methane production typically begins within the first year after the waste is disposed of in a landfill and will continue for 10 to 50 or more years as the degradable waste decomposes over time.

In 2020, landfill CH_4 emissions were approximately 109.3 MMT CO_2 Eq. (4,373 kt), representing the third largest source of CH_4 emissions in the United States, behind enteric fermentation and natural gas systems. Emissions from MSW landfills accounted for approximately 86 percent of total landfill emissions (94.2 MMT CO_2 Eq.), while industrial waste landfills accounted for the remainder (15.1 MMT CO_2 Eq.). Nationally, there are significantly less industrial waste landfills (hundreds) compared to MSW landfills (thousands), which contributes to the lower national estimate of CH_4 emissions for industrial waste landfills. Additionally, the average organic content of waste streams disposed in industrial waste landfills is lower than MSW landfills. Estimates of operational MSW landfills in the United States have ranged from 1,700 to 2,000 facilities (EPA 2021a; EPA 2021b; EPA 2019; Waste Business Journal [WBJ] 2016; WBJ 2010). The Environment Research & Education Foundation (EREF) conducted a

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[1] For more information regarding federal MSW landfill regulations, see http://www.epa.gov/osw/nonhaz/municipal/landfill/msw_regs.htm.

nationwide analysis of MSW management and counted 1,540 operational MSW landfills in 2013 (EREF 2016). Conversely, there are approximately 3,200 MSW landfills in the United States that have been closed since 1980 (for which a closure data is known, (EPA 2021b; WBJ 2010). While the number of active MSW landfills has decreased significantly over the past 20 years, from approximately 6,326 in 1990 to as few as 1,540 in 2013, the average landfill size has increased (EPA 2021a; EREF 2016; BioCycle 2010). Larger landfills may have deeper cells where a greater amount of area will be anaerobic (more CH_4 is generated in anaerobic versus aerobic areas) and larger landfills tend to generate more CH_4 compared to a smaller landfill (assuming the same waste composition and age of waste). Regarding industrial waste landfills, the WBJ database includes approximately 1,200 landfills accepting industrial and/or construction and demolition debris for 2016 (WBJ 2016). Only 169 facilities with industrial waste landfills met the reporting threshold under Subpart TT (Industrial Waste Landfills) in the first year (2011) of EPA's Greenhouse Gas Reporting Program for this subpart (GHGRP codified in 40 CFR part 98), indicating that there may be several hundred industrial waste landfills that are not required to report under EPA's GHGRP. Less industrial waste landfills meet the GHGRP eligibility threshold because they typically accept waste streams with low to no organic content, which will not decompose and generate CH_4 when disposed.

The annual amount of MSW generated and subsequently disposed in MSW landfills varies annually and depends on several factors (e.g., the economy, consumer patterns, recycling and composting programs, inclusion in a garbage collection service). The estimated annual quantity of waste placed in MSW landfills increased 10 percent from approximately 205 MMT in 1990 to 226 MMT in 2000, then decreased by 11 percent to 202 MMT in 2010, and then increased by 6 percent to approximately 214 MMT in 2020 (see Annex 3.14, Table A-220). Emissions decreased between 1990 to 2010 largely because of increased use of landfill gas collection and control systems, closure of older landfills, better management practices, and increased diversion of organics through state and local policy and regulations. The total amount of MSW generated is expected to increase as the U.S. population continues to grow, but the percentage of waste landfilled may decline due to increased recycling and composting practices. The impacts of the coronavirus (COVID-19) pandemic with respect to landfilled waste cannot be quantified until data sources such as the EPA's *Advancing Sustainable Materials Management: Facts and Figures* report are published for 2019 and 2020. The quantities of waste landfilled for 2014 to 2020 (presented in Annex 3.14) are extrapolated based on population growth and the last national assessment of MSW landfilled from 2013 (EREF 2016). Net CH_4 emissions from MSW landfills have decreased since 1990 (see Table 7-3 and Table 7-4).

The estimated quantity of waste placed in industrial waste landfills (from the pulp and paper, and food processing sectors) has remained relatively steady since 1990, ranging from 9.7 MMT in 1990 to 10.3 MMT in 2020 (see Annex 3.14, Table A-219). CH_4 emissions from industrial waste landfills have also remained at similar levels recently, ranging from 14.4 MMT CO_2 Eq. in 2005 to 15.1 MMT CO_2 Eq. in 2020 when accounting for both CH_4 generation and oxidation. The EPA has focused the industrial waste landfills source category on industrial sectors known to generate and dispose of by-products that are organic and contribute to CH_4 generation, which are the pulp and paper and food processing sectors. Construction and demolition (C&D) landfills, another type of industrial waste landfill, may accept waste that could degrade (e.g., treated wood), but these waste streams are unlikely to generate significant amounts of CH_4 and are therefore not as relevant to the purpose of national greenhouse gas emissions estimate. There is also a general lack of data on annual quantities of waste disposed in industrial waste landfills and the GHGRP Subpart TT (Industrial Waste Landfills) dataset has confirmed C&D landfills, for example, are insignificant CH_4 generators.

EPA's Landfill Methane Outreach Program (LMOP) collects information on landfill gas energy projects currently operational or under construction throughout the United States. LMOP's Landfill and Landfill Gas Energy Database contains certain information on the gas collection and control systems in place at landfills provided by organizations that are a part of the program, which can include the amount of landfill gas collected and flared. In 2020, LMOP identified 6 new landfill gas-to-energy (LFGE) projects (EPA 2021b) that began operation. While the amount of landfill gas collected and combusted continues to increase, the rate of increase in collection and combustion no longer exceeds the rate of additional CH_4 generation from the amount of organic MSW landfilled as the U.S. population grows (EPA 2021a).

Landfill gas collection and control is not accounted for at industrial waste landfills in this chapter (see the Methodology discussion for more information).

Table 7-3: CH_4 Emissions from Landfills (MMT CO_2 Eq.)

Activity	1990	2005	2016	2017	2018	2019	2020
MSW CH_4 Generation[a]	205.3	271.1	283.0	291.8	297.0	304.6	304.8
Industrial CH_4 Generation	12.1	16.0	16.6	16.7	16.7	16.7	16.8
MSW CH_4 Recovered[a]	(21.3)	(132.5)	(165.9)	(172.1)	(174.1)	(179.6)	(184.1)
MSW CH_4 Oxidized[a]	(18.4)	(21.4)	(24.1)	(25.5)	(26.2)	(26.5)	(26.6)
Industrial CH_4 Oxidized	(1.2)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
MSW net CH_4 Emissions	165.7	117.2	93.0	94.2	96.7	98.6	94.2
Industrial CH_4 Emissions[b]	10.9	14.4	15.0	15.0	15.0	15.1	15.1
Total	**176.6**	**131.5**	**107.9**	**109.2**	**111.7**	**113.6**	**109.3**

[a] For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2020, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2020 (EPA 2021a).

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 7-4: CH_4 Emissions from Landfills (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
MSW CH_4 Generation[a]	8,214	10,845	11,321	11,672	11,878	12,186	12,193
Industrial CH_4 Generation	484	638	666	667	668	669	672
MSW CH_4 Recovered[a]	(851)	(5,301)	(6,637)	(6,884)	(6,965)	(7,182)	(7,362)
MSW CH_4 Oxidized[a]	(736)	(856)	(965)	(1,020)	(1,046)	(1,061)	(1,063)
Industrial CH_4 Oxidized	(48)	(64)	(67)	(67)	(67)	(67)	(67)
MSW net CH_4 Emissions	6,627	4,687	3,719	3,768	3,867	3,943	3,768
Industrial net CH_4 Emissions[b]	436	575	599	600	601	602	605
Total	**7,063**	**5,262**	**4,318**	**4,368**	**4,467**	**4,545**	**4,373**

[a] For years 1990 to 2004, the Inventory methodology for MSW landfills uses the first order decay methodology. A methodological change occurs in year 2005. For years 2005 to 2020, directly reported net CH_4 emissions from the GHGRP data plus a scale-up factor are used to account for emissions from landfill facilities that are not subject to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. These data incorporate CH_4 recovered and oxidized for MSW landfills. As such, CH_4 generation, CH_4 oxidation, and CH_4 recovery are not calculated separately and totaled to net CH_4 emissions. See the Methodology and Time-Series Consistency section of this chapter for more information.

[b] Methane recovery is not calculated for industrial landfills because this is not a common practice in the United States. Only 1 landfill of 169 that report to Subpart TT (Industrial Waste Landfills) of the GHGRP had an active gas collection and control system during the year 2020 (EPA 2021a).

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology and Time-Series Consistency

Methodology Applied for MSW Landfills

A combination of IPCC Tier 2 and 3 approaches (IPCC 2006) are used to calculate emissions from MSW Landfills.

Methane emissions from landfills are estimated using two primary methods. The first method uses the first order decay (FOD) model as described by the *2006 IPCC Guidelines* to estimate CH_4 generation. The amount of CH_4 recovered and combusted from MSW landfills is subtracted from the CH_4 generation and is then adjusted with an oxidation factor. The oxidation factor represents the amount of CH_4 in a landfill that is oxidized to CO_2 as it passes through the landfill cover (e.g., soil, clay, geomembrane). This method is presented below and is similar to Equation HH-6 in 40 CFR Part 98.343 for MSW landfills, and Equation TT-6 in 40 CFR Part 98.463 for industrial waste landfills.

Equation 7-1: Landfill Methane Generation

$$\mathrm{CH}_{4,\mathrm{MSW}} = \left(G_{CH4} - \textstyle\sum_{n-1}^{N} R_n\right) * (1 - OX)$$

where,

$\mathrm{CH}_{4,\mathrm{MSW}}$ = Net CH_4 emissions from solid waste
$\mathrm{G}_{\mathrm{CH4,MSW}}$ = CH_4 generation from MSW landfills, using emission factors for DOC, k, MCF, F from IPCC (2006) and other peer-reviewed sources
R = CH_4 recovered and combusted
Ox = CH_4 oxidized from MSW landfills before release to the atmosphere, using Ox values from IPCC (2006) and other peer-reviewed or scientifically validated literature (40 CFR Part 98)

The second method used to calculate CH_4 emissions from landfills, also called the back-calculation method, is based on directly measured amounts of recovered CH_4 from the landfill gas and is expressed below and by Equation HH-8 in 40 CFR Part 98.343. The two parts of the equation consider the portion of CH_4 in the landfill gas that is not collected by the landfill gas collection system, and the portion that is collected. First, the recovered CH_4 is adjusted with the collection efficiency of the gas collection and control system and the fraction of hours the recovery system operated in the calendar year. This quantity represents the amount of CH_4 in the landfill gas that is not captured by the collection system; this amount is then adjusted for oxidation. The second portion of the equation adjusts the portion of CH_4 in the collected landfill gas with the efficiency of the destruction device(s), and the fraction of hours the destruction device(s) operated during the year.

Equation 7-2: Net Methane Emissions from MSW Landfills

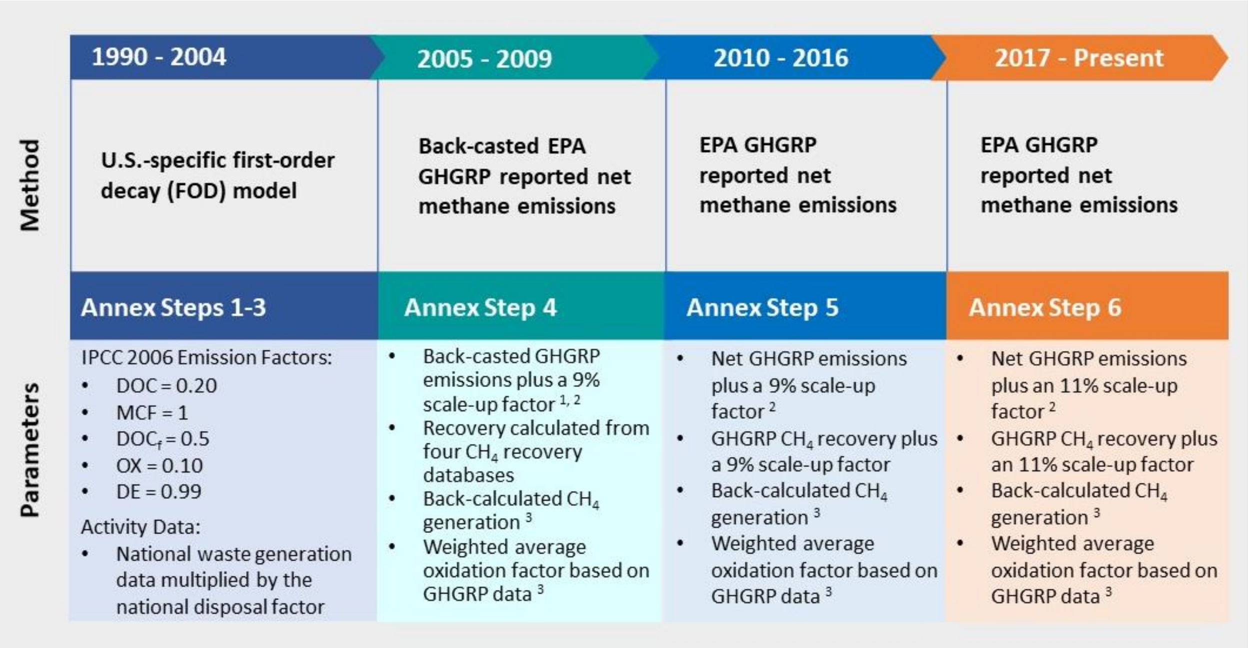
$$\mathrm{CH}_{4,\text{Solid Waste}} = [\left(\frac{R}{CE\ x\ f_{REC}} - R\right) x(1 - OX) + R\ x\ \left(1 - (DE\ x\ f_{Dest})\right)]$$

where,

$\mathrm{CH}_{4,\text{Solid Waste}}$ = Net CH_4 emissions from solid waste
R = Quantity of recovered CH_4 from Equation HH-4 of EPA's GHGRP
CE = Collection efficiency estimated at the landfill, considering system coverage, operation, and cover system materials from Table HH-3 of EPA's GHGRP. If area by soil cover type information is not available, the default value of 0.75 should be used (percent)
f_{REC} = fraction of hours the recovery system was operating (percent)
OX = oxidation factor (percent)
DE = destruction efficiency (percent)
f_{Dest} = fraction of hours the destruction device was operating (fraction)

The current Inventory uses both methods to estimate CH_4 emissions across the time series within EPA's Waste Model, as summarized in Figure 7-3 below. This chapter provides a summary of the methods, activity data, and parameters used. Additional step-wise explanations to generate the net emissions are provided in Annex 3.14.

Figure 7-3: Methodologies Used Across the Time Series to Compile the U.S. Inventory of Emission Estimates for MSW Landfills



	1990 - 2004	2005 - 2009	2010 - 2016	2017 - Present
Method	U.S.-specific first-order decay (FOD) model	Back-casted EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions	EPA GHGRP reported net methane emissions
	Annex Steps 1-3	Annex Step 4	Annex Step 5	Annex Step 6
Parameters	IPCC 2006 Emission Factors: • DOC = 0.20 • MCF = 1 • DOC_f = 0.5 • OX = 0.10 • DE = 0.99 Activity Data: • National waste generation data multiplied by the national disposal factor	• Back-casted GHGRP emissions plus a 9% scale-up factor [1, 2] • Recovery calculated from four CH_4 recovery databases • Back-calculated CH_4 generation [3] • Weighted average oxidation factor based on GHGRP data [3]	• Net GHGRP emissions plus a 9% scale-up factor [2] • GHGRP CH_4 recovery plus a 9% scale-up factor • Back-calculated CH_4 generation [3] • Weighted average oxidation factor based on GHGRP data [3]	• Net GHGRP emissions plus an 11% scale-up factor [2] • GHGRP CH_4 recovery plus an 11% scale-up factor • Back-calculated CH_4 generation [3] • Weighted average oxidation factor based on GHGRP data [3]

[1] The intent of the scale-up factor is to estimate emissions from landfills that do not report to the GHGRP. More details on the scale-up factor and how it was developed can be found in Annex 3.14. The back-casted emissions are calculated using directly reported net methane emissions for GHGRP reporting years 2010 to 2016. The back-casted emissions are subject to change in each Inventory based on new reporting year reports and resubmitted greenhouse gas reports for previous years. This method is compatible with the *2006 IPCC Guidelines* because facilities reporting to the GHGRP either use the FOD method, or directly measured methane recovery data with default emission factors either directly included in the *2006 IPCC Guidelines* or scientifically validated through peer review.

[2] Emission factors used by facilities reporting to GHGRP Subpart HH are facility-specific defaults derived from peer-reviewed literature and the *2006 IPCC Guidelines*.

[3] Methane generation is back-calculated from the net MSW emissions, estimated methane recovery data, and the weighted average oxidation factor based on GHGRP Subpart HH reported data of 0.18 between 2010 to 2016, and 0.21 between 2017 to present.

The Waste Model is a spreadsheet developed by the IPCC for purposes of estimating methane emissions from solid waste disposal sites, adapted to the United States by the inclusion and usage of U.S.-specific parameters. The Waste Model contains activity and waste generation information from both the MSW and Industrial landfill sectors and estimates the amount of CH_4 emissions from each sector for each year of the time series, using both methods. Prior to the 1990 through 2015 Inventory, only the FOD method was used. Methodological changes were made to the 1990 through 2015 Inventory to incorporate higher tier data (i.e., CH_4 emissions as directly reported to EPA's GHGRP), which cannot be directly applied to earlier years in the time series without significant bias. The technique used to merge the directly reported GHGRP data with the previous methodology is described as the overlap technique in the Time-Series Consistency chapter of the *2006 IPCC Guidelines*. Additional details on the technique used is included in Annex 3.14, and a technical memorandum (RTI 2017).

A summary of the methodology used to generate the current 1990 through 2020 Inventory estimates for MSW landfills is as follows and is also illustrated in Annex Figure A-19:

- **1940 to 1989:** These years are included for historical waste disposal amounts. Estimates of the annual quantity of waste landfilled for 1960 through 1988 were obtained from EPA's Anthropogenic Methane Emissions in the United States, Estimates for 1990: Report to Congress (EPA 1993) and an extensive landfill survey by the EPA's Office of Solid Waste in 1986 (EPA 1988). Although waste placed in landfills in the 1940s and 1950s contributes very little to current CH_4 generation, estimates for those years were included in the FOD model for completeness in accounting for CH_4 generation rates and are based on the population in those years and the per capita rate for land disposal for the 1960s. For the Inventory calculations, wastes landfilled prior to 1980 were broken into two groups: wastes disposed in managed, anaerobic landfills (Methane Conversion Factor, MCF, of 1) and those disposed in uncategorized solid waste disposal waste sites (MCF of 0.6) (IPCC 2006). Uncategorized sites represent those sites for which limited information is known about the management practices. All calculations after 1980 assume waste is disposed in managed, anaerobic landfills. The FOD method was applied to estimate annual CH_4 generation. Methane recovery amounts were then subtracted, and the result was then adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Step 1.

- **1990 to 2004:** The Inventory time series begins in 1990. The FOD method is exclusively used for this group of years. The national total of waste generated (based on state-specific landfill waste generation data) and a national average disposal factor for 1989 through 2004 were obtained from the State of Garbage (SOG) survey every two years (i.e., 2002, 2004 as published in BioCycle 2006). In-between years were interpolated based on population growth. For years 1989 to 2000, directly reported total MSW generation data were used; for other years, the estimated MSW generation (excluding construction and demolition waste and inerts) were presented in the reports and used in the Inventory. The FOD method was applied to estimate annual CH_4 generation. Landfill-specific CH_4 recovery amounts (calculated from four CH_4 recovery databases) were then subtracted from CH_4 generation and the result was adjusted with a 10 percent oxidation factor to derive the net emissions estimates. A detailed explanation of the methods used are presented in Annex 3.14 Steps 1 through 3.
- **2005 to 2009:** Emissions for these years are estimated using net CH_4 emissions that are reported by landfill facilities under EPA's GHGRP. Because not all landfills in the United States are required to report to EPA's GHGRP, a 9 percent scale-up factor is applied to the GHGRP emissions for completeness. The intent of the scale-up factor is to account for emissions from landfills that do not report to the GHGRP. Supporting information, including details on the technique used to estimate emissions for 2005 to 2009, to develop the scale-up factor, and to ensure time-series consistency by incorporating the directly reported GHGRP emissions is presented in Annex 3.14 Step 4 and in RTI 2018a. Separate estimates of CH_4 generation, CH_4 recovery, and oxidation are calculated from the net CH_4 emissions. Landfill-specific CH_4 recovery is calculated from four CH_4 recovery databases. A single oxidation factor is not applied to the annual CH_4 generated as is done for 1990 to 2004 because the GHGRP emissions data are used, which already take oxidation into account. The GHGRP allows facilities to use varying oxidation factors (i.e., 0, 10, 25, or 35 percent) depending on their facility-specific calculated CH_4 flux rate. The effectively applied average oxidation factor between 2005 to 2009 averages to 0.14. Methane generation is then back-calculated using net CH_4 emissions, CH_4 recovery, and oxidation. A detailed explanation of the methods used to develop the back-casted emissions and revised scale-up factor are presented in Annex 3.14 Step 4.
- **2010 to 2016:** Net CH_4 emissions as directly reported to the GHGRP are used with a 9 percent scale-up factor to account for landfills that are not required to report to the GHGRP. A combination of the FOD method and the back-calculated CH_4 emissions were used by the facilities reporting to the GHGRP. Landfills reporting to the GHGRP without gas collection and control apply the FOD method, while most landfills with landfill gas collection and control apply the back-calculation method. Methane recovery is calculated using reported GHGRP recovery data plus a 9 percent scale-up factor. Methane generation and oxidation are back-calculated from the net GHGRP CH_4 emissions applied and estimated CH_4 recovery. The average oxidation factor effectively applied is 0.18 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 5.
- **2017 to 2020:** The same methodology is applied as for 2010 through 2016 where a scale-up factor is applied to account for landfills that are not required to report to the GHGRP. The scale-up factor was revised for the current (1990 to 2020) Inventory to change the methodology from total waste-in-place to only considering waste disposed for non-reporting landfills in the past 50 years (i.e., since 1970).

> Additional revisions made included incorporating facilities that have stopped reporting to the GHGRP, new additions to the 2021 LMOP Database (EPA 2021b), corrections to the underlying database of non-reporting landfills used to develop the 9 percent scale-up factor that were identified. For 2017 to 2020, a scale-up factor of 11 percent is applied annually to the GHGRP net reported CH_4 emissions. Methane recovery is calculated using reported GHGRP recovery data plus an 11 percent scale-up factor. Separate estimates of CH_4 generation and oxidation are calculated from the net CH_4 emissions applied. The average oxidation factor effectively applied is 0.21 percent. A detailed explanation of the methods used to develop the revised scale-up factor are presented in Annex 3.14 Step 6.

With regard to the time series and as stated in *2006 IPCC Guidelines Volume 1: Chapter 5 Time-Series Consistency* (IPCC 2006), “the time series is a central component of the greenhouse gas inventory because it provides information on historical emissions trends and tracks the effects of strategies to reduce emissions at the national level. All emissions in a time series should be estimated consistently, which means that as far as possible, the time series should be calculated using the same method and data sources in all years” (IPCC 2006). In some cases it may not be possible to use the same methods and consistent data sets for all years because of limited data (activity data, emission factors, or other parameters) directly used in the calculation of emission estimates for some historical years. In such cases, emissions or removals may need to be recalculated using alternative methods. In this case, this chapter provides guidance on techniques to splice, or join methodologies together instead of back-casting emissions back to 1990. One of those techniques is referred to as the overlap technique. The overlap technique is recommended when new data becomes available for multiple years. This was the case with EPA’s GHGRP data for MSW landfills, where directly reported CH_4 emissions data became available for more than 1,200 MSW landfills beginning in 2010. The GHGRP emissions data had to be merged with emissions from the FOD method to avoid a drastic change in emissions in 2010, when the datasets were combined. EPA also had to consider that according to IPCC’s good practice, efforts should be made to reduce uncertainty in Inventory calculations and that, when compared to the GHGRP data, the FOD method presents greater uncertainty.

In evaluating the best way to combine the two datasets, EPA considered either using the FOD method from 1990 to 2009, or using the FOD method for a portion of that time and back-casting the GHGRP emissions data to a year where emissions from the two methodologies aligned. Plotting the back-casted GHGRP emissions against the emissions estimates from the FOD method showed an alignment of the data in 2004 and later years which facilitated the use of the overlap technique while also reducing uncertainty. A detailed explanation and a chart showing the estimates across the time series considering the two method options is included in Annex 3.14. EPA ultimately decided to back-cast the GHGRP emissions from 2009 to 2005 only, to merge the datasets and adhere to the IPCC *Good Practice Guidance* for ensuring time-series consistency.

Supporting information, including details on the techniques used to ensure time-series consistency by incorporating the directly-reported GHGRP emissions is presented in Annex 3.14.

Methodology Applied for Industrial Waste Landfills

Emissions from industrial waste landfills are estimated using a Tier 2 approach (IPCC 2006) and a tailored (country-specific) IPCC waste model. Activity data used are industrial production data (ERG 2021) for two sectors (pulp and paper manufacturing, and food and beverage manufacturing) to which country-specific default waste disposal factors are applied (a separate disposal factor for each sector). The disposal factors, as described below, are based on scientifically reviewed data, and are the same across the entire time series. The emission factors are based on those recommended by the *2006 IPCC Guidelines* and are the same across the entire time series.

The FOD equation from IPCC 2006 is used via the waste model to estimate methane emissions:

Equation 7-3: Net Methane Emissions from Industrial Waste Landfills

$$CH_{4,IND} = (G_{CH4} - \sum_{n-1}^{N} R_n) * (1 - OX)$$

where,

$CH_{4,Solid\ Waste}$ = Net CH_4 emissions from solid waste

$G_{CH4,Ind}$ = CH_4 generation from industrial waste landfills, using production data multiplied by a disposal factor and emission factors for DOC, k, MCF, F (IPCC 2006)
R = CH_4 recovered and combusted (no recovery is assumed for industrial waste landfills)
OX = CH_4 oxidized from industrial waste landfills before release to the atmosphere (using the *2006 IPCC Guidelines* value for OX of 0.10)

The activity data used in the emission calculations are production data (e.g., the amount of meat, poultry, vegetables processed; the amount of paper produced) versus disposal data. There are currently no facility-specific data sources that track and report the amount and type of waste disposed of in the universe of industrial waste landfills in the United States. EPA's GHGRP provides some insight into waste disposal in industrial waste landfills but is not comprehensive. Data reported to the GHGRP on industrial waste landfills suggests that most of the organic waste which would result in methane emissions is disposed at pulp and paper and food processing facilities. Of the 168 facilities that reported to Subpart TT of the GHGRP in 2019, 92 (54 percent) are in the North American Industrial Classification System (NAICS) for Pulp, Paper, and Wood Products (NAICS 321 and 322) and 12 (7 percent) are in Food Manufacturing (NAICS 311).

Based on this limited information, the Inventory methodology assumes most of the organic waste placed in industrial waste landfills originates from the food processing (meat, vegetables, fruits) and pulp and paper sectors, thus estimates of industrial landfill emissions focused on these two sectors. EPA validated this assumption through an analysis of the Subpart TT of the GHGRP in the 2016 reporting year (RTI 2018b). The Subpart TT waste disposal information for pulp and paper facilities correlates well with the activity data currently used to estimate Inventory emissions; however, the waste disposal information in Subpart TT related to food and beverage facilities are approximately an order of magnitude different than the Inventory disposal estimates for the entire time series.

EPA conducted a literature review in 2020 to investigate other sources of industrial food waste, which is briefly described in the Planned Improvements section, and decided to maintain the currently used methodology for the previous 1990 through 2019 Inventory due to questions around data availability across the 1990 to 2019 time series, the completeness and representativeness of other estimates and methodologies, and the level of effort required to reproduce and/or merge estimates across the 1990 to 2019 time series.

The composition of waste disposed of in industrial waste landfills is expected to be more consistent in terms of composition and quantity than that disposed of in MSW landfills. The amount of waste landfilled is assumed to be a fraction of production that is held constant over the time series as explained in Annex 3.14.

Landfill CH_4 recovery is not accounted for in industrial waste landfills. Data collected through EPA's GHGRP for industrial waste landfills (Subpart TT) show that only one of the 166 facilities, or 1 percent of facilities, have active gas collection systems (EPA 2021a). However, because EPA's GHGRP is not a national database and comprehensive data regarding gas collection systems have not been published for industrial waste landfills, assumptions regarding a percentage of landfill gas collection systems, or a total annual amount of landfill gas collected for the non-reporting industrial waste landfills have not been made for the Inventory methodology.

The amount of CH_4 oxidized by the landfill cover at industrial waste landfills was assumed to be 10 percent of the CH_4 generated (IPCC 2006; Mancinelli and McKay 1985; Czepiel et al. 1996) for all years.

Box 7-3: Nationwide Municipal Solid Waste Data Sources

Municipal solid waste (MSW) generated in the United States can be managed through a variety of methods. MSW that is not recycled, composted (and later land applied), combusted with energy recovery, or digested is assumed to be landfilled. In addition to these management pathways, waste or excess food from the food manufacturing and processing sector may be disposed through the sewerage network, used for animal feed, donated for human consumption, and rendered or recycled into biofuels in the case of animal by-products, fats, oils and greases.

There have been three main sources for nationwide solid waste management data in the United States that the Inventory has used (see Annex 3.14, Box A-3 for comparison of estimates from these data sources):

- The *BioCycle* and Earth Engineering Center of Columbia University's SOG in America surveys [no longer published];
- The EPA's *Advancing Sustainable Materials Management: Facts and Figures* reports; and
- The EREF's *MSW Generation in the United States* reports.

The SOG surveys and, most recently EREF, collected state-reported data on the amount of waste generated and the amount of waste managed via different management options: landfilling, recycling, composting, and combustion. These data sources used a 'bottom-up' method. The survey asked for actual tonnages instead of percentages in each waste category (e.g., residential, commercial, industrial, construction and demolition, organics, tires) for each waste management option. If such a breakdown was not available, the survey asked for total tons landfilled. The data were adjusted for imports and exports across state lines so that the principles of mass balance were adhered to for completeness, whereby the amount of waste managed did not exceed the amount of waste generated. The SOG and EREF reports present survey data aggregated to the state level.

The EPA *Advancing Sustainable Materials Management: Facts and Figures* reports use a materials flow methodology, commonly referred to as a 'top-down' methodology, which relies heavily on a mass balance approach. Data are gathered from industry associations, key businesses, similar industry sources, and government agencies (e.g., the Department of Commerce and the U.S. Census Bureau) and are used to estimate tons of materials and products generated, recycled, combusted with energy recovery, other food management pathways, or landfilled nationwide. The amount of MSW generated is estimated by estimating production and then adjusting these values by addressing the imports and exports of produced materials to other countries. MSW that is not recycled or composted is assumed to be combusted or landfilled, except for wasted food, which uses a different methodology and includes nine different management pathways. The 2018 Facts and Figures Report (U.S. EPA 2020) uses a methodology that expanded the number of management pathways to include: animal feed; bio-based materials/biochemical processing (i.e., rendering); codigestion/anaerobic digestion; composting/aerobic processes; combustion; donation; land application; landfill; and sewer/wastewater treatment.

In this Inventory, emissions from solid waste management are presented separately by waste management option, except for recycling of waste materials. Emissions from recycling are attributed to the stationary combustion of fossil fuels that may be used to power on-site recycling machinery and are presented in the stationary combustion chapter in the Energy sector, although the emissions estimates are not called out separately. Emissions from solid waste disposal in landfills and the composting of solid waste materials are presented in the Landfills and Composting sections in the Waste sector of this report. Emissions from anaerobic digesters are presented in three different sections depending on the digester category. Emissions from on-farm digesters are included in the Agriculture sector; emissions from digesters at wastewater treatment plants emissions from stand-alone digesters are presented in separate sections in the Waste sector of this report. In the United States, almost all incineration of MSW occurs at waste-to-energy (WTE) facilities or industrial facilities where useful energy is recovered, and thus emissions from waste incineration are accounted for in the Incineration chapter of the Energy sector of this report.

Uncertainty

Several types of uncertainty are associated with the estimates of CH_4 emissions from MSW and industrial waste landfills when the FOD method is applied directly for 1990 to 2004 in the Waste Model and, to some extent, in the GHGRP methodology. The approach used in the MSW emission estimates assumes that the CH_4 generation potential (L_o) and the rate of decay that produces CH_4 from MSW, as determined from several studies of CH_4 recovery at MSW landfills, are representative of conditions at U.S. MSW landfills. When this top-down approach is applied at the nationwide level, the uncertainties are assumed to be less than when applying this approach to individual landfills and then aggregating the results to the national level. In other words, the FOD method as applied in this Inventory is not facility-specific modeling and while this approach may over- or underestimate CH_4

generation at some landfills if used at the facility-level, the result is expected to balance out because it is being applied nationwide.

There is a high degree of uncertainty associated with the FOD model, particularly when a homogeneous waste composition and hypothetical decomposition rates are applied to heterogeneous landfills (IPCC 2006). There is less uncertainty in EPA's GHGRP data because this methodology is facility-specific, uses directly measured CH_4 recovery data (when applicable), and allows for a variety of landfill gas collection efficiencies, destruction efficiencies, and/or oxidation factors to be used.

Uncertainty also exists in the scale-up factors (both 9 percent and 11 percent) applied for years 2005 to 2016 and 2017 to 2020, respectively, and in the back-casted emissions estimates for 2005 to 2009. As detailed in RTI (2018a), limited information is available for landfills that do not report to the GHGRP. RTI developed an initial list of landfills that do not report to the GHGRP with the intent of quantifying the total waste-in-place for these landfills that would add up to the scale-up factor. Input was provided by industry, LMOP, and additional EPA support. However, many gaps existed in the initial development of this Non-Reporting Landfills Database. Assumptions were made for hundreds of landfills to estimate their waste-in-place and the subsequent scale-up factors. The waste-in-place estimated for each landfill is likely not 100 percent accurate and should be considered a reasonable estimate. Additionally, a simple methodology was used to back-cast emissions for 2005 to 2009 using the GHGRP-reported emissions from 2010 to 2020. This methodology does not factor in annual landfill to landfill changes in landfill CH_4 generation and recovery. Because of this, an uncertainty factor of 25 percent is applied to the scale-up factor and years (emission estimates) the scale-up factor is applied to.

Aside from the uncertainty in estimating landfill CH_4 generation, uncertainty also exists in the estimates of the landfill gas oxidized at MSW landfills. Facilities directly reporting to EPA's GHGRP can use oxidation factors ranging from 0 to 35 percent, depending on their facility-specific CH_4 flux. As recommended by the *2006 IPCC Guidelines* for managed landfills, a 10 percent default oxidation factor is applied in the Inventory for both MSW landfills (those not reporting to the GHGRP and for the years 1990 to 2004 when GHGRP data are not available) and industrial waste landfills regardless of climate, the type of cover material, and/or presence of a gas collection system.

Another significant source of uncertainty lies with the estimates of CH_4 recovered by flaring and gas-to-energy projects at MSW landfills that are sourced from the Inventory's CH_4 recovery databases (used for years 1990 to 2004). Four CH_4 recovery databases are used to estimate nationwide CH_4 recovery for MSW landfills for 1990 to 2009. The GHGRP MSW landfills database was added as a fourth recovery database starting with the 1990 to 2013 Inventory report (two years before the full GHGRP data set started being used for net CH_4 emissions for the Inventory). Relying on multiple databases for a complete picture introduces uncertainty because the coverage and characteristics of each database differs, which increases the chance of double counting avoided emissions. The methodology and assumptions that go into each database differ. For example, the flare database assumes the midpoint of each flare capacity at the time it is sold and installed at a landfill; the flare may be achieving a higher capacity, in which case the flare database would underestimate the amount of CH_4 recovered. Additionally, two databases, the EIA database and flare vendor database, could no longer be updated for the entire time series due to external factors. For example, the EIA database has not been updated since 2006 because the EIA stopped collected landfill recovery data. The EIA database has, for the most part, been replaced by the GHGRP MSW landfills database. The flare database was populated annually until 2015, but decreasing, voluntary participation from flare vendors sharing their flare sales data for several years prior to 2015.

To avoid double counting and to use the most relevant estimate of CH_4 recovery for a given landfill, a hierarchical approach is used among the four databases. GHGRP data and the EIA data are given precedence because facility data were directly reported; the LFGE data are given second priority because CH_4 recovery is estimated from facility-reported LFGE system characteristics; and the flare data are given the lowest priority because this database contains minimal information about the flare, no site-specific operating characteristics, and includes smaller landfills not included in the other three databases (Bronstein et al. 2012). The coverage provided across the databases most likely represents the complete universe of landfill CH_4 gas recovery; however, the number of unique landfills between the four databases does differ.

The *2006 IPCC Guidelines* default value of 10 percent for uncertainty in recovery estimates was used for two of the four recovery databases in the uncertainty analysis where metering of landfill gas was in place (for about 64 percent of the CH_4 estimated to be recovered). This 10 percent uncertainty factor applies to the LFGE database; 12 percent to the EIA database; and 1 percent for the GHGRP MSW landfills dataset because of the supporting information provided and rigorous verification process. For flaring without metered recovery data (the flare database), a much higher uncertainty value of 50 percent is used. The compounding uncertainties associated with the four databases in addition to the uncertainties associated with the FOD method and annual waste disposal quantities leads to the large upper and lower bounds for MSW landfills presented in Table 7-5.

The lack of landfill-specific information regarding the number and type of industrial waste landfills in the United States is a primary source of uncertainty with respect to the industrial waste generation and emission estimates. The approach used here assumes that most of the organic waste disposed of in industrial waste landfills that would result in CH_4 emissions consists of waste from the pulp and paper and food processing sectors. However, because waste generation and disposal data are not available in an existing data source for all U.S. industrial waste landfills, a straight disposal factor is applied over the entire time series to the amount produced to determine the amounts disposed. Industrial waste facilities reporting under EPA's GHGRP do report detailed waste stream information, and these data have been used to improve, for example, the DOC value used in the Inventory methodology for the pulp and paper sector. A 10 percent oxidation factor is also applied to CH_4 generation estimates for industrial waste landfills and carries the same amount of uncertainty as with the factor applied to CH_4 generation for MSW landfills.

The results of the *2006 IPCC Guidelines* Approach 2 quantitative uncertainty analysis are summarized in Table 7-5. There is considerable uncertainty for the MSW landfills estimates due to the many data sources used, each with its own uncertainty factor.

Table 7-5: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Landfills	**CH_4**	**109.3**	**84.7**	**133.3**	**-23%**	**22%**
MSW	CH_4	94.2	73.7	123.0	-22%	31%
Industrial	CH_4	15.1	10.4	18.9	-31%	25%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval. Individual uncertainty factors are applied to activity data and emission factors in the Monte Carlo analysis.

QA/QC and Verification

General quality assurance/quality control (QA/QC) procedures were applied consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Vol. 1, Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). QA/QC checks are performed for the transcription of the published data set (e.g., EPA's GHGRP dataset) used to populate the Inventory data set in terms of completeness and accuracy against the reference source. Additionally, all datasets used for this category have been checked to ensure they are of appropriate quality and are representative of U.S. conditions. The primary calculation spreadsheet is tailored from the *2006 IPCC Guidelines* waste model and has been verified previously using the original, peer-reviewed IPCC waste model. All model input values and calculations were verified by secondary QA/QC review. Stakeholder engagements sessions in 2016 and 2017 were used to gather input on methodological improvements and facilitate an external expert review on the methodology, activity data, and emission factors.

Category-specific checks include the following:

- Evaluation of the secondary data sources used as inputs to the Inventory dataset to ensure they are appropriately collected and are reliable;

- Cross-checking the data (activity data and emissions estimates) with previous years to ensure the data are reasonable, and that any significant variation can be explained through the activity data;
- Conducting literature reviews to evaluate the appropriateness of country-specific emission factors (e.g., DOC values, precipitation zones with respect to the application of the k values) given findings from recent peer-reviewed studies; and
- Reviewing secondary datasets to ensure they are nationally complete and supplementing where necessary (e.g., using a scale-up factor to account for emissions from landfills that do not report to EPA's GHGRP).

A primary focus of the QA/QC checks in past Inventories was to ensure that CH_4 recovery estimates were not double-counted and that all LFGE projects and flares were included in the respective project databases. QA/QC checks performed in the past for the recovery databases were not performed in this Inventory, because new data were not added to the recovery databases in this Inventory year.

For the GHGRP data, EPA verifies annual facility-level reports through a multi-step process (e.g., combination of electronic checks and manual reviews by staff) to identify potential errors and ensure that data submitted to EPA are accurate, complete, and consistent.[2] Based on the results of the verification process, EPA follows up with facilities to resolve mistakes that may have occurred. The post-submittals checks are consistent with several general and category-specific QC procedures, including range checks, statistical checks, algorithm checks, and year-to-year checks of reported data and emissions. For the MSW Landfills sector, under Subpart HH of the GHGRP, MSW Landfills with gas collection are required to report emissions from their site using both a forward- (using a first order decay model as a basis) and back-calculating (using parameters specific to the landfill itself, such as measured recovery and collection efficiency of the landfill gas) methodology. Details on the forward- and back-calculation approach can be found in Annex 3.14 and 40 CFR Subpart HH of Part 98. Reporters can choose which of these two methodologies they believe best represents the emissions at their landfill and are required to submit that value as their total Subpart HH emissions. Facilities are generally not expected to switch between the two equations each year, as the emissions calculated using each method can vary greatly and can have a significant effect on emission trends for that landfill, and potentially the entire MSW Landfill sector under the GHGRP. Key checks are in place to assure that emissions are trending in a sensible way year over year for each reporting landfill.

For the current (1990 to 2020) Inventory, the scale-up factor methodology was revised from a total waste-in-place comparison to a time-based threshold (50-years) for waste disposed between landfills that do and do not report to Subpart HH of the GHGRP. An 11 percent scale-up factor resulted from the time-based threshold (between 1970 to 2020). This value is the same scale-up factor as that calculated when considering the total waste-in-place scale-up factor incorporated into the previous 1990 through 2019 Inventory for 2017 to 2019. Additional details about the scale-up factor are presented in Annex 3.14.

Recalculations Discussion

Revisions to the individual facility reports submitted to EPA's GHGRP can be made at any time and a portion of facilities have revised their reports since 2010 for various reasons, resulting in changes to the total net CH_4 emissions for MSW landfills. Each Inventory year, the back-casted emissions for 2005 to 2009 will be recalculated using the most recently verified data from the GHGRP. Changes in these data result in changes to the back-casted emissions. The impact of the revisions to the GHGRP Subpart HH annual greenhouse gas reports resubmitted for 2015 to 2019 slightly increased or decreased total Subpart HH reported net emissions by ± 0.3 percent in the years the Subpart HH data are applied (i.e., 2005 to 2019). No Subpart HH reports were resubmitted for the 2010 to 2014 reporting years that resulted in net emission changes. These changes resulted in annual increases of less than

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[2] See https://www.epa.gov/sites/production/files/2015-07/documents/ghgrp_verification_factsheet.pdf.

0.2 percent to the net Inventory emissions between 2005 to 2009, and annual decreases of less than 1 percent per year to the net Inventory emissions between 2015 to 2019. A change in net Subpart HH reported emissions results in the same percentage change in the Inventory emissions for that year.

The scale-up factor was also reassessed as a planned improvement for the current (1990 to 2020) Inventory. Results from this effort did not change the 11 percent scale-up factor that was applied between 2017 to 2019 in the current 1990 to 2020 inventory.

Planned Improvements

EPA received recommendations from industry stakeholders regarding the DOC values and decay rates (k values) required to be used in the GHGRP calculations. Stakeholders have suggested that newer, more up-to-date default values considering recent trends in the composition of waste disposed in MSW landfills for both k and DOC in the GHGRP should be developed and reflected in the 2005 and later years of the Inventory. In response, EPA is developing a multivariate analysis using publicly available Subpart HH GHGRP data, solving for optimized DOC and k values across the more than 1,100 landfills reporting to the program. The results of this analysis could help inform future GHGRP rulemaking where changes could be made to the default DOC and k values contained within Subpart HH, which could then be carried over to the Inventory emissions estimates for MSW landfills upon promulgation of any revisions to 40 CFR part 98. This potential improvement may be long-term.

With respect to the scale-up factor, EPA received comments on revisions made to the scale-up for the 1990 to 2020 inventory from a total waste-in-place approach to a time-based threshold of 50 years. Commenters noted that this time-based threshold approach does not adjust for the non-linearity of methane production of landfill gas. In response, EPA will further investigate how best to account for emissions from MSW landfills that do not report to the GHGRP, including using the FOD model for these landfills based on estimated annual waste disposed for this subset of landfills between 2005 to 2020, reverting to the total waste-in-place approach, or modifying the time-based threshold approach. Any methodological revisions to accounting for emissions from this subset of landfills will be made in next (1990 to 2021) inventory.

Relatedly, EPA will periodically assess the impact to the waste-in-place and emissions data from GHGRP facilities that have resubmitted annual reports during any reporting years, are new reporting facilities, and from facilities that have stopped reporting to the GHGRP to ensure national estimates are as complete as possible. Facilities may stop reporting to the GHGRP when they meet the “off-ramp” provisions (reported less than 15,000 metric tons of CO_2 equivalent emissions for 3 consecutive years or less than 25,000 metric tons of CO_2 equivalent emissions for 5 consecutive years). As was the case with this Inventory, if warranted, EPA will revise the scale-up factor to reflect newly acquired information to ensure completeness of the Inventory. For this inventory, EPA considered public comments received on the 1990-2019 inventory specific to using a time-based threshold to calculate the scale-up factor instead of a total waste-in-place approach. The rationale supporting the comments was that older, closed landfills with large quantities of waste-in-place are driving up the scale=up factor, but have little impact on total methane generation. EPA assessed two time-based scenarios for developing the scale-up factor – one scenario looking at the past 30 years of waste disposed, and the second looking at the past 50 years of waste disposed.

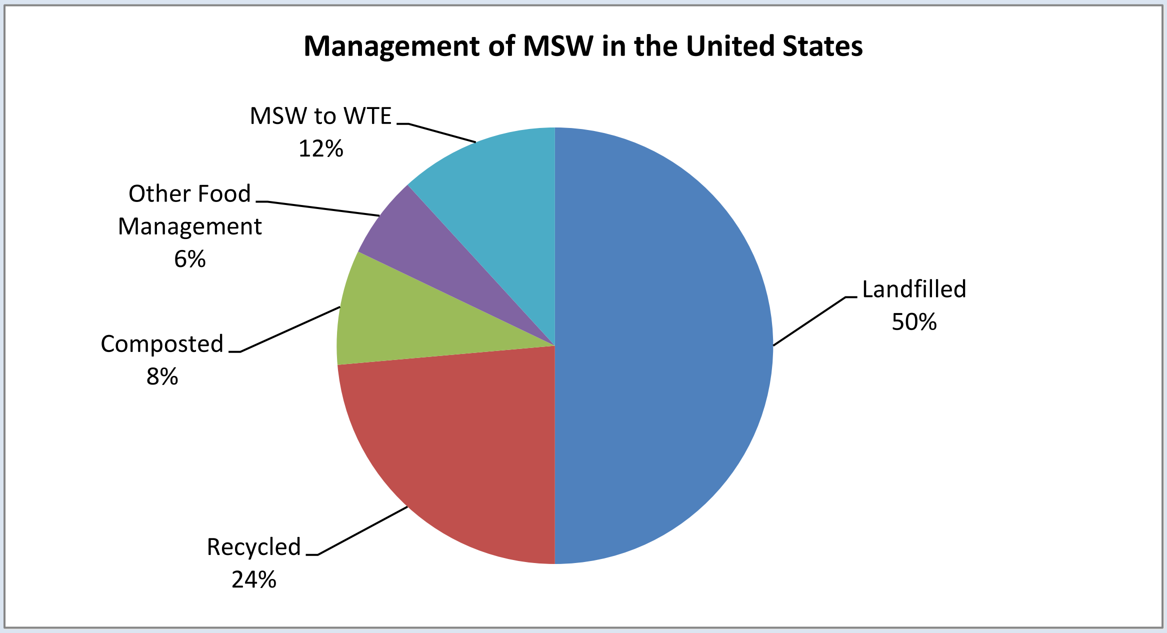
EPA is planning to account for unmanaged landfills in Puerto Rico and other U.S. Territories to the landfill emissions estimates. Data limitations for the history of waste received at these sites make this challenging. Presently emissions from managed sites in Puerto Rico and Guam are accounted for years 2005 to present as they are reporters to GHGRP Subpart HH.

Additionally, with the recent publication of the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019), EPA will begin to update applicable emission factors, methodologies, and assumptions underlying emission estimates for landfills and make any applicable changes during the next (1990 to 2021) Inventory cycle per the *2019 Refinement*.

Box 7-4: Overview of U.S. Solid Waste Management Trends

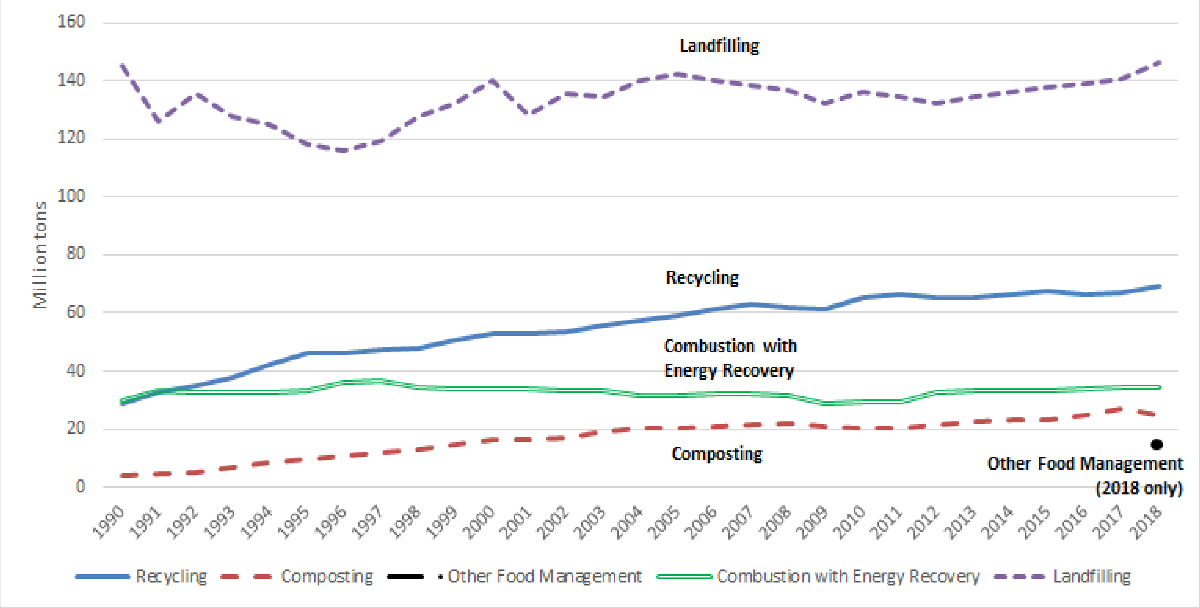
As shown in Figure 7-4 and Figure 7-5, landfilling of MSW is currently and has been the most common waste management practice. A large portion of materials in the waste stream are recovered for recycling and composting, which is becoming an increasingly prevalent trend throughout the country. Materials that are composted and recycled would have previously been disposed in a landfill.

Figure 7-4: Management of Municipal Solid Waste in the United States, 2018



Source: EPA (2020b)
Note: 2018 is the latest year of available data. Data taken from Table 35 of EPA (2020a). MSW to WTE is combustion with energy recovery (WTE = waste-to-energy).

Figure 7-5: MSW Management Trends from 1990 to 2018



Source: EPA (2020b). The EPA Advancing Sustainable Materials Management reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA 2020b for 1990,

2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request but are no longer on the EPA's Advancing Sustainable Materials Management web site.[3]
Note: 2018 is the latest year of available data. Only one year of data (2018) is available for the 'Other Food Management' category.

Table 7-6 presents the average composition of waste disposed in a typical MSW landfill in the United States over time. It is important to note that the actual composition of waste entering each landfill will vary from that presented in Table 7-6. Due to China's recent ban on accepting certain kinds of solid waste by the end of 2017 (WTO 2017), inclusive of some paper and paperboard waste, plastic waste, and other miscellaneous inorganic wastes, there has been a slight increase in the disposal of paper and paperboard and plastic wastes since 2017 (Table 7-6). Future impacts of China's recent waste ban to the composition of waste disposed in U.S. landfills are unknown at this time.

Understanding how the waste composition changes over time, specifically for the degradable waste types (i.e., those types known to generate CH_4 as they break down in a modern MSW landfill), is important for estimating greenhouse gas emissions. Increased diversion of degradable materials so that they are not disposed of in landfills reduces the CH_4 generation potential and CH_4 emissions from landfills. For certain degradable waste types (i.e., paper and paperboard), the amounts discarded have decreased over time due to an increase in waste diversion through recycling and composting (see Table 7-6 and Figure 7-6). As shown in Figure 7-6, the diversion of food scraps has been consistently low since 1990 because most cities and counties do not practice curbside collection of these materials, although the quantity has been slowly increasing in recent years. Neither Table 7-6 nor Figure 7-6 reflect the frequency of backyard composting of yard trimmings and food waste because this information is largely not collected nationwide and is hard to estimate.

Table 7-6: Materials Discarded in the Municipal Waste Stream by Waste Type from 1990 to 2018 (Percent)

Waste Type	1990	2005	2015	2016	2017	2018
Paper and Paperboard	30.0%	24.7%	13.3%	12.7%	13.1%	11.8%
Glass	6.0%	5.8%	5.0%	4.9%	4.9%	5.2%
Metals	7.2%	7.9%	9.5%	9.8%	9.9%	9.5%
Plastics	9.5%	16.4%	18.9%	18.9%	19.2%	18.5%
Rubber and Leather	3.2%	2.9%	3.3%	3.4%	3.5%	3.4%
Textiles	2.9%	5.3%	7.7%	8.0%	8.0%	7.7%
Wood	6.9%	7.5%	8.0%	8.8%	8.7%	8.3%
Other	1.4%	1.8%	2.2%	2.2%	2.2%	2.0%
Food Scraps	13.6%	18.5%	22.0%	22.1%	22.0%	24.1%
Yard Trimmings	17.6%	7.0%	7.8%	6.9%	6.2%	7.2%
Miscellaneous Inorganic Wastes	1.7%	2.2%	2.3%	2.3%	2.3%	2.3%

Source: EPA (2020b)

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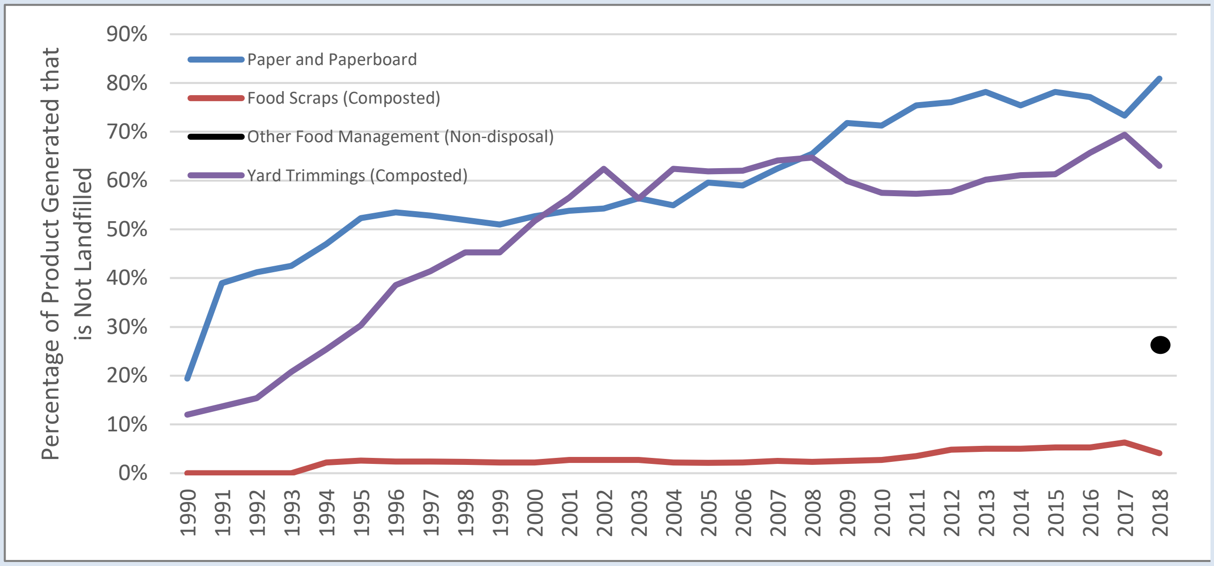
[3] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

Figure 7-6: Percent of Degradable Materials Diverted from Landfills from 1990 to 2018 (Percent)



Source: EPA (2020b). The EPA Advancing Sustainable Materials reports only present data for select years, thus several reports were used in the compilation of this figure. All data were taken from Table 35 in EPA (2020b) for 1990, 2000, 2015, 2017 and 2018. Data were taken from Table 35 in EPA (2019) for 2010 and 2016. Data were taken from EPA (2018) for 2014. Data were taken from Table 35 of EPA (2016b) for 2012 and 2013. Data were taken from Table 30 of EPA (2014) for 2008 and 2011. The reports with data available for years prior to EPA (2012) can be provided upon request, but are not longer on the EPA's Advancing Sustainable Materials Management web site.[4]

Note: The data shown in this chart are for recycling of paper and paperboard, composting of food scraps and yard trimmings, and alternative management pathways for the Other Food Management (non-disposal) category. The Other Food Management (non-disposal) category is a new addition and only one year of data are available for 2018 (28 percent of the food waste generated was beneficially reused or managed using a method that was not landfilling, recycling, or composting). The Other Food Management pathways include animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment.

7.2 Wastewater Treatment and Discharge (CRF Source Category 5D)

Wastewater treatment and discharge processes are sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. Wastewater from domestic and industrial sources is treated to remove soluble organic matter, suspended solids, nutrients, pathogenic organisms, and chemical contaminants.[5] Treatment of domestic wastewater may either occur on site, most commonly through septic systems, or off site at centralized treatment systems, most commonly at publicly owned treatment works (POTWs). In the United States, approximately 18

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[4] See https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

[5] Throughout the Inventory, emissions from domestic wastewater also include any commercial and industrial wastewater collected and co-treated with domestic wastewater.

percent of domestic wastewater is treated in septic systems or other on-site systems, while the rest is collected and treated centrally (U.S. Census Bureau 2019). Treatment of industrial wastewater may occur at the industrial plant using package or specially designed treatment plants or be collected and transferred off site for co-treatment with domestic wastewater in centralized treatment systems.

Centralized Treatment. Centralized wastewater treatment systems use sewer systems to collect and transport wastewater to the treatment plant. Sewer collection systems provide an environment conducive to the formation of CH_4, which can be substantial depending on the configuration and operation of the collection system (Guisasola et al. 2008). Recent research has shown that at least a portion of CH_4 formed within the collection system enters the centralized system where it contributes to CH_4 emissions from the treatment system (Foley et al. 2015).

The treatment plant may include a variety of processes, ranging from physical separation of material that readily settles out (typically referred to as primary treatment), to treatment operations that use biological processes to convert and remove contaminants (typically referred to as secondary treatment), to advanced treatment for removal of targeted pollutants, such as nutrients (typically referred to as tertiary treatment). Not all wastewater treatment plants conduct primary treatment prior to secondary treatment, and not all plants conduct advanced or tertiary treatment (EPA 1998a).

Soluble organic matter is generally removed using biological processes in which microorganisms consume the organic matter for maintenance and growth. Microorganisms can biodegrade soluble organic material in wastewater under aerobic or anaerobic conditions, where the latter condition produces CH_4. The resulting biomass (sludge) is removed from the effluent prior to discharge to the receiving stream and may be further biodegraded under aerobic or anaerobic conditions, such as anaerobic sludge digestion. Sludge can be produced from both primary and secondary treatment operations. Some wastewater may also be treated using constructed (or semi-natural) wetland systems, though it is much less common in the United States and represents a relatively small portion of wastewater treated centrally (<0.1 percent) (ERG 2016). Constructed wetlands are a coupled anaerobic-aerobic system and may be used as the primary method of wastewater treatment, or are more commonly used as a final treatment step following settling and biological treatment. Constructed wetlands develop natural processes that involve vegetation, soil, and associated microbial assemblages to trap and treat incoming contaminants (IPCC 2014). Constructed wetlands do not produce secondary sludge (sewage sludge).

The generation of N_2O may also result from the treatment of wastewater during both nitrification and denitrification of the nitrogen (N) present, usually in the form of urea, proteins, and ammonia. Ammonia N is converted to nitrate (NO_3) through the aerobic process of nitrification. Denitrification occurs under anoxic/anaerobic conditions, whereby anaerobic or facultative organisms reduce oxidized forms of nitrogen (e.g., nitrite, nitrate) in the absence of free oxygen to produce nitrogen gas (N_2). Nitrous oxide is generated as a by-product of nitrification, or as an intermediate product of denitrification. No matter where N_2O is formed it is typically stripped (i.e., transferred from the liquid stream to the air) in aerated parts of the treatment process. Stripping also occurs in non-aerated zones at rates lower than in aerated zones.

On-site Treatment. The vast majority of on-site systems in the United States are septic systems composed of a septic tank, generally buried in the ground, and a soil dispersion system. Solids and dense materials contained in the incoming wastewater (influent) settle in the septic tank as sludge. Floatable material (scum) is also retained in the tank. The sludge that settles on the bottom of the tank undergoes anaerobic digestion. Partially treated water is discharged in the soil dispersal system. The solid fraction accumulates and remains in the tank for several years, during which time it degrades anaerobically. The gas produced from anaerobic sludge digestion (mainly CH_4 and biogenic CO_2) rises to the liquid surface and is typically released through vents. The gas produced in the effluent dispersal system (mainly N_2O and biogenic CO_2) is released through the soil.

Discharge. Dissolved CH_4 and N_2O that is present in wastewater discharges to aquatic environments has the potential to be released (Short et al. 2014; Short et al. 2017), and the addition of organic matter or nitrogen from wastewater discharges is generally expected to increase CH_4 and N_2O emissions from these environments. Where organic matter is released to slow-moving aquatic systems, such as lakes, estuaries, and reservoirs, CH_4 emissions are expected to be higher. Similarly, in the case of discharge to nutrient-impacted or hypoxic waters, N_2O emissions can be significantly higher.

The principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material in the wastewater. Common parameters used to measure the organic component of the wastewater are the biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Under the same conditions, wastewater with higher COD (or BOD) concentrations will generally yield more CH_4 than wastewater with lower COD (or BOD) concentrations. BOD represents the amount of oxygen that would be required to completely consume the organic matter contained in the wastewater through aerobic decomposition processes, while COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20°C, or BOD_5. Throughout the rest of this chapter, the term "BOD" refers to BOD_5. Because BOD is an aerobic parameter, it is preferable to use COD to estimate CH_4 production, since CH_4 is produced only in anaerobic conditions. Where present, biogas recovery and flaring operations reduce the amount of CH_4 generated that is actually emitted. Per IPCC guidelines (IPCC 2019), emissions from anaerobic sludge digestion, including biogas recovery and flaring operations, where the digester's primary use is for treatment of wastewater treatment solids, are reported under Wastewater Treatment. The principal factor in determining the N_2O generation potential of wastewater is the amount of N in the wastewater. The variability of N in the influent to the treatment system, as well as the operating conditions of the treatment system itself, also impact the N_2O generation potential.

In 2020, CH_4 emissions from domestic wastewater treatment and discharge were estimated to be 10.0 MMT CO_2 Eq. (400 kt CH_4) and 1.8 MMT CO_2 Eq. (73 kt CH_4), respectively. Emissions remained fairly steady from 1990 through 2002 but have decreased since that time due to decreasing percentages of wastewater being treated in anaerobic systems, generally including reduced use of on-site septic systems and central anaerobic treatment systems (EPA 1992, 1996, 2000, and 2004a; U.S. Census Bureau 2019). In 2020, CH_4 emissions from industrial wastewater treatment and discharge were estimated to be 5.9 MMT CO_2 Eq. (238 kt CH_4) and 0.5 MMT CO_2 Eq. (20 kt CH_4), respectively. Industrial emissions from wastewater treatment have generally increased across the time series through 1999 and then fluctuated up and corresponding with production changes from the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and brewery industries. Industrial wastewater emissions have generally seen an uptick since 2016. However, in 2020, some industries (including starch-based ethanol production and petroleum refining), experienced a more significant decrease in production (and, by extension, emissions) due to the COVID-19 pandemic (see Table 7-20). Table 7-7 and Table 7-8 provide CH_4 emission estimates from domestic and industrial wastewater treatment.

With respect to N_2O, emissions from domestic wastewater treatment and discharge in 2020 were estimated to be 18.1 MMT CO_2 Eq. (61 kt N_2O) and 4.9 MMT CO_2 Eq. (16 kt N_2O), respectively. Total N_2O emissions from domestic wastewater were estimated to be 23.0 MMT CO_2 Eq. (77 kt N_2O). Nitrous oxide emissions from wastewater treatment processes gradually increased across the time series as a result of increasing U.S. population and protein consumption. In 2020, N_2O emissions from industrial wastewater treatment and discharge were estimated to be 0.4 MMT CO_2 Eq. (1 kt N_2O) and 0.1 MMT CO_2 Eq. (0.3 kt N_2O), respectively. Industrial emission sources have gradually increased across the time series with production changes associated with the treatment of wastewater from the pulp and paper manufacturing, meat and poultry processing, petroleum refining, and brewery industries, though see the CH_4 discussion above regarding 2020 industrial production. Table 7-7 and Table 7-8 provide N_2O emission estimates from domestic wastewater treatment.

Table 7-7: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (MMT CO_2 Eq.)

Activity	1990		2005		2016	2017	2018	2019	2020
CH_4	**20.3**		**20.1**		**18.7**	**18.5**	**18.3**	**18.1**	**18.3**
Domestic Treatment	13.5		12.9		10.8	10.5	10.2	9.8	10.0
Domestic Effluent	1.2		1.2		1.8	1.8	1.8	1.8	1.8
Industrial Treatment[a]	4.9		5.4		5.6	5.7	5.8	5.9	5.9
Industrial Effluent[a]	0.7		0.6		0.5	0.5	0.5	0.5	0.5
N_2O	**16.6**		**20.3**		**22.8**	**23.2**	**23.5**	**23.4**	**23.5**

Domestic Treatment	11.8	15.4	17.3	17.7	18.0	18.0	18.1
Domestic Effluent	4.4	4.4	5.0	5.0	5.0	4.9	4.9
Industrial Treatment[b]	0.3	0.4	0.4	0.4	0.4	0.5	0.4
Industrial Effluent[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**36.9**	**40.5**	**41.5**	**41.7**	**41.8**	**41.5**	**41.8**

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Note: Totals may not sum due to independent rounding.

Table 7-8: CH_4 and N_2O Emissions from Domestic and Industrial Wastewater Treatment (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
CH_4	**812**	**806**	**748**	**740**	**732**	**723**	**730**
Domestic Treatment	540	518	434	420	407	393	400
Domestic Effluent	49	49	71	72	73	73	73
Industrial Treatment[a]	196	216	223	228	232	237	238
Industrial Effluent[a]	27	22	20	20	20	20	20
N_2O	**56**	**68**	**76**	**78**	**79**	**79**	**79**
Domestic Treatment	40	52	58	59	60	60	61
Domestic Effluent	15	15	17	17	17	16	16
Industrial Treatment[b]	1	1	1	1	2	2	1
Industrial Effluent[b]	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] Industrial activity for CH_4 includes the pulp and paper manufacturing, meat and poultry processing, fruit and vegetable processing, starch-based ethanol production, petroleum refining, and breweries industries.

[b] Industrial activity for N_2O includes the pulp and paper manufacturing, meat and poultry processing, starch-based ethanol production, and petroleum refining.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodologies presented in IPCC (2019) form the basis of the CH_4 and N_2O emission estimates for both domestic and industrial wastewater treatment and discharge.[6] Domestic wastewater treatment follows the IPCC Tier 2 methodology for key pathways, while domestic wastewater discharge follows IPCC Tier 2 discharge methodology and emission factors. Default factors from IPCC (2019) or IPCC (2006) are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor, though IPCC default factors are often based in part on data from or representative of U.S. wastewater treatment systems. Industrial wastewater treatment follows IPCC Tier 1 and wastewater treatment discharge follows Tier 1 or Tier 2 methodologies, depending on the industry. EPA will continue to implement the Tier 2 discharge methodology for more industries as data are investigated and time and resource constraints allow (see the Planned Improvements section below). Similar to domestic wastewater, IPCC default factors are used when there are insufficient U.S.-specific data to develop a U.S.-specific factor.

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[6] IPCC (2019) updates, supplements, and elaborates the *2006 IPCC Guidelines* where gaps or out-of-date science have been identified. EPA used these methodologies to improve completeness and include sources of greenhouse gas emissions that have not been estimated prior to the 1990-2019 Inventory, such as N_2O emissions from industrial wastewater treatment, and to improve emission estimates for other sources, such as emissions from wastewater discharge and centralized wastewater treatment.

Methodological approaches were applied to the entire time series to ensure consistency in emissions from 1990 through 2020. In the following cases, the source used to capture activity data changed over the time series. EPA recognizes this may appear to lower data consistency; however, believes the result is more accurate. For example:

- Starch-based ethanol production data: the source used for 1990 to 2017 production was no longer available after 2017. A new, publicly available source was identified and is used for production in 2018-2020. However, this source does not have sufficient data for the earlier timeseries. EPA confirmed with experts familiar with the sources that combining these two sources to populate the time series was accurate (ERG 2019; Lewis 2019) and does not present any significant discontinuities in the time series.
- Brewery production data: the source used for production changed in 2007 to publish craft brewery production broken out by size but does not include data prior to 2007. Therefore, rather than estimating total production data prior to 2007, another data source was used to ensure accuracy of production data through the time series (ERG 2018b).

Refer to the Recalculations section below for details on updates implemented to improve accuracy, consistency and/or completeness of the time series.

Domestic Wastewater CH_4 Emission Estimates

Domestic wastewater CH_4 emissions originate from both septic systems and from centralized treatment systems. Within these centralized systems, CH_4 emissions can arise from aerobic systems that liberate dissolved CH_4 that formed within the collection system or that are designed to have periods of anaerobic activity (e.g., constructed wetlands and facultative lagoons), anaerobic systems (anaerobic lagoons and anaerobic reactors), and from anaerobic sludge digesters when the captured biogas is not completely combusted. Emissions will also result from the discharge of treated effluent from centralized wastewater plants to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries). The systems with emissions estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C);
- Anaerobic sludge digesters (D); and
- Centralized wastewater treatment effluent (E).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic CH_4 emissions are estimated as follows:

Equation 7-4: Total Domestic CH_4 Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic CH}_4\text{ Emissions from Wastewater Treatment and Discharge (kt)} = \mathrm{A} + \mathrm{B} + \mathrm{C} + \mathrm{D} + \mathrm{E}$$

Table 7-9 presents domestic wastewater CH_4 emissions for both septic and centralized systems, including anaerobic sludge digesters and emissions from centralized wastewater treatment effluent, in 2020.

Table 7-9: Domestic Wastewater CH_4 Emissions from Septic and Centralized Systems (2020, kt, MMT CO_2 Eq. and Percent)

	CH_4 Emissions (kt)	CH_4 Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater CH_4
Septic Systems (A)	227	5.7	48.0
Centrally-Treated Aerobic Systems (B)	37	0.9	7.8
Centrally-Treated Anaerobic Systems (C)	127	3.2	26.9
Anaerobic Sludge Digesters (D)	8	0.2	1.7
Centrally-Treated Wastewater Effluent (E)	73	1.8	15.5
Total	**473**	**11.8**	**100**

Emissions from Septic Systems:

Methane emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 17 percent in 2020; U.S. Census Bureau 2019) and an emission factor and then converting the result to kt/year.

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2021) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. Table 7-12 presents U.S. population for 1990 through 2020. The fraction of the U.S. population using septic systems or centralized treatment systems is based on data from the *American Housing Surveys* (U.S. Census Bureau 2019). Methane emissions for septic systems are estimated as follows:

Equation 7-5: CH_4 Emissions from Septic Systems

$$\textit{Emissions from Septic Systems}\ (\text{U.S. Specific}) = \text{A}$$
$$= \text{US}_{\text{POP}} \times (\text{T}_{\text{SEPTIC}}) \times (\text{EF}_{\text{SEPTIC}}) \times 1/10^9 \times 365.25$$

Table 7-10: Variables and Data Sources for CH_4 Emissions from Septic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	1990-2020: U.S. Census Bureau (2021)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020: Forecasted from the rest of the time series
EF_{SEPTIC}	Methane emission factor – septic systems (10.7)	g CH_4/capita/day	1990-2020: Leverenz et al. (2010)
$1/10^9$	Conversion factor	g to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Methane emissions from POTWs depend on the total organics in wastewater. Table 7-12 presents total BOD_5 produced (also referred to as the total organically degradable material in wastewater or TOW) for 1990 through 2020. The BOD_5 production rate was determined using BOD generation rates per capita weighted average both with and without kitchen scraps as well as an estimated percent of housing units that utilize kitchen garbage disposals. Households with garbage disposals (with kitchen scraps or ground up food scraps) typically have wastewater with higher BOD than households without garbage disposals due to increased organic matter contributions (ERG 2018a). The equations are as follows:

Equation 7-6: Total Wastewater BOD_5 Produced per Capita (U.S.-Specific [ERG 2018a])

$$\text{BOD}_{\text{gen rate}}\ (\text{kg/capita/day}) = \text{BOD}_{\text{without scrap}} \times (1 - \%\text{disposal}) + \text{BOD}_{\text{with scraps}} \times (\%\text{disposal})$$

Equation 7-7: Total Organically Degradable Material in Domestic Wastewater (IPCC 2019 [Eq. 6.3])

$$\text{TOW (Gg/year)} = \text{US}_{\text{POP}} \times \text{BOD}_{\text{gen rate}} \times 365.25$$

Table 7-11: Variables and Data Sources for Organics in Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
$BOD_{gen\ rate}$	Total wastewater BOD produced per capita	kg/capita/day	1990-2020: Calculated
$BOD_{without\ scrap}$	Wastewater BOD produced per capita without kitchen scraps[a]	kg/capita/day	1990-2003: Metcalf & Eddy (2003) 2004-2013: Linear interpolation 2014-2020: Metcalf & Eddy (2014)
$BOD_{with\ scraps}$	Wastewater BOD produced per capita with kitchen scraps[a]	kg/capita/day	
% disposal	Percent of housing units with kitchen disposal[a]	%	1990-2013: U.S. Census Bureau (2013) 2014-2020: Forecasted from the rest of the time series
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2020: Calculated, ERG (2018a)
US_{POP}	U.S. population[a]	Persons	1990-2020: U.S. Census Bureau (2021)
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of activity data varies over the Inventory time series.

Table 7-12: U.S. Population (Millions) and Domestic Wastewater BOD_5 Produced (kt)

Activity	1990	2005	2016	2017	2018	2019	2020
Population	253	300	327	329	330	332	336
TOW	8,131	9,624	9,816	9,891	9,956	10,017	10,164

Sources: U.S. Census Bureau (2021); ERG (2018a).

Methane emissions from POTWs were estimated by multiplying the total organics in centrally treated wastewater (total BOD_5) produced per capita in the United States by the percent of wastewater treated centrally, or percent collected (about 83 percent in 2020), the correction factor for additional industrial BOD discharged to the sewer system, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands), constructed wetlands only, and anaerobic systems, and the emission factor[7] for aerobic systems, constructed wetlands only, and anaerobic systems. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

In the United States, the removal of sludge[8] from wastewater reduces the biochemical oxygen demand of the wastewater that undergoes aerobic treatment. The amount of this reduction (S) is estimated using the default IPCC methodology (IPCC 2019) and multiplying the amount of sludge removed from wastewater treatment in the United States by the default factors in IPCC (2019) to estimate the amount of BOD removed based on whether the treatment system has primary treatment with no anaerobic sludge digestion (assumed to be zero by expert judgment), primary treatment with anaerobic sludge digestion, or secondary treatment without primary treatment. The organic component removed from anaerobic wastewater treatment and the amount of CH_4

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[7] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of domestic wastewater (B_0, 0.6 kg CH_4/kg BOD) and the appropriate methane correction factors (MCF) for aerobic (0.03) and anaerobic (0.8) systems (IPCC 2019) and constructed wetlands (0.4) (IPCC 2014).

[8] Throughout this document, the term “sludge” refers to the solids separated during the treatment of municipal wastewater. The definition includes domestic septage. “Biosolids” refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal.

recovered or flared from both aerobic and anaerobic wastewater treatment were set equal to the IPCC default of zero.

The methodological equations for CH_4 emissions from aerobic and anaerobic systems are:

Equation 7-8: Total Domestic CH_4 Emissions from Centrally Treated Aerobic Systems

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)}\ (\mathrm{B1}) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)}\ (\mathrm{B2}) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)}\ (\mathrm{B3}) = \mathrm{B}$$

where,

Equation 7-9: Total Organics in Centralized Wastewater Treatment [IPCC 2019 (Eq. 6.3A)]

$$TOW_{CENTRALIZED}\ (\mathrm{Gg\ BOD/year}) = \mathrm{TOW} \times \mathrm{T_{CENTRALIZED}} \times \mathrm{I_{COLLECTED}}$$

Table 7-13: Variables and Data Sources for Organics in Centralized Domestic Wastewater

Variable	Variable Description	Units	Inventory Years: Source of Value
Centrally Treated Organics (Gg BOD/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2020: Calculated
TOW	Total wastewater BOD Produced per Capita[a]	Gg BOD/year	1990-2020: Calculated, ERG (2018a)
$T_{CENTRALIZED}$	Percent collected[a]	%	1990-2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020: Forecasted from the rest of the time series
$I_{COLLECTED}$	Correction factor for additional industrial BOD discharged (1.25)	No units	1990-2020: IPCC (2019)

[a] Value of this activity data varies over the time series.

Equation 7-10: Organic Component Removed from Aerobic Wastewater Treatment (IPCC 2019 [Eq. 6.3B])

$$\mathrm{S_{aerobic}}\ (\mathrm{Gg/year}) = \mathrm{S_{mass}} \times [(\%\ \mathrm{aerobic\ w/primary} \times \mathrm{K_{rem,aer\_prim}}) + (\%\ \mathrm{aerobic\ w/out\ primary} \times \mathrm{K_{rem,aer\_noprim}}) + (\%\mathrm{aerobic{+}digestion} \times \mathrm{K_{rem,aer\_digest}})] \times 1000$$

Equation 7-11: Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.1])

$$\mathrm{B1}\ (\mathrm{kt\ CH_4/year}) = [(\mathrm{TOW_{CENTRALIZED}}) \times (\%\ \mathrm{aerobic_{OTCW}}) - \mathrm{S_{aerobic}}] \times \mathrm{EF_{aerobic}} - \mathrm{R_{aerobic}}$$

Table 7-14: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt CH_4/year)			
$S_{aerobic}$	Organic component removed from aerobic wastewater treatment[a]	Gg BOD/year	1990-2020: Calculated
S_{mass}	Raw sludge removed from wastewater treatment as dry mass[a]	Tg dry weight/year	1988: EPA (1993c); EPA (1999) 1990-1995: Calculated based on sewage sludge production change per year EPA (1993c); EPA (1999); Beecher et al. (2007)

Variable	Variable Description	Units	Inventory Years: Source of Value
			1996: EPA (1999) 2004: Beecher et al. (2007) Data for intervening years obtained by linear interpolation 2005-2020: Forecasted from the rest of the time series
% $\text{aerobic}_{\text{OTCW}}$	Percent of flow to aerobic systems, other than wetlands[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2020: Forecasted from the rest of the time series
% aerobic w/primary	Percent of aerobic systems with primary treatment and no anaerobic sludge digestion (0)	%	
% aerobic w/out primary	Percent of aerobic systems without primary treatment[a]	%	
%aerobic+digestion	Percent of aerobic systems with primary and anaerobic sludge digestion[a]	%	
$K_{\text{rem,aer\_prim}}$	Sludge removal factor for aerobic treatment plants with primary treatment (mixed primary and secondary sludge, untreated or treated aerobically) (0.8)	kg BOD/kg sludge	1990-2020: IPCC (2019)
$K_{\text{rem,aer\_noprim}}$	Sludge removal factor for aerobic wastewater treatment plants without separate primary treatment (1.16)	kg BOD/kg sludge	
$K_{\text{rem,aer\_digest}}$	Sludge removal factor for aerobic treatment plants with primary treatment and anaerobic sludge digestion (mixed primary and secondary sludge, treated anaerobically) (1)	kg BOD/kg sludge	
1000	Conversion factor	metric tons to kilograms	
EF_{aerobic}	Emission factor – aerobic systems (0.018)	kg CH_4/kg BOD	
R_{aerobic}	Amount CH_4 recovered or flared from aerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Constructed wetlands exhibit both aerobic and anaerobic treatment (partially anaerobic treatment) but are referred to in this chapter as aerobic systems. Constructed wetlands may be used as the sole treatment unit at a centralized wastewater treatment plant or may serve as tertiary treatment after simple settling and biological treatment. Emissions from all constructed wetland systems were included in the estimates of emissions from centralized wastewater treatment plant processes and effluent from these plants. Methane emissions equations from constructed wetlands used as sole treatment were previously described. Methane emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow from treatment to constructed wetlands, wastewater BOD concentration entering tertiary treatment, constructed wetlands emission factor, and then converting to kt/year.

For constructed wetlands, an IPCC default emission factor for surface flow wetlands was used. This is the most conservative factor for constructed wetlands and was recommended by IPCC (2014) when the type of constructed wetland is not known. A median BOD_5 concentration of 9.1 mg/L was used for wastewater entering constructed wetlands used as tertiary treatment based on U.S. secondary treatment standards for POTWs. This median value is based on plants generally utilizing simple settling and biological treatment (EPA 2013). Constructed wetlands do not have secondary sludge removal.

Equation 7-12: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) [IPCC 2014 (Eq. 6.1)]

$$\text{B2 (kt CH}_4\text{/year)} = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\text{aerobic}_{\text{CW}})] \times (\text{EF}_{\text{CW}})$$

Equation 7-13: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S. Specific)

$$\text{B3 (kt CH}_4\text{/year)} = [(\text{POTW\_flow\_CW}) \times (\text{BOD}_{\text{CW,INF}}) \times 3.785 \times (\text{EF}_{\text{CW}})] \times 1/10^6 \times 365.25$$

Table 7-15: Variables and Data Sources for CH_4 Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2020: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs.[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2020: IPCC (2014)
Emissions from Constructed Wetlands used as Tertiary Treatment (kt CH_4/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
$BOD_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (9.1)	mg/L	1990-2020: EPA (2013)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.24)	kg CH_4/kg BOD	1990-2020: IPCC (2014)
$1/10^6$	Conversion factor	kg to kt	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the time series.

Data sources and methodologies for centrally treated anaerobic systems are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-14: Emissions from Centrally Treated Anaerobic Systems [IPCC 2019 (Eq. 6.1)]

$$\text{C (kt CH}_4\text{/year)} = [(\text{TOW}_{\text{CENTRALIZED}}) \times (\%\text{ anaerobic}) - \text{S}_{\text{anaerobic}}] \times \text{EF}_{\text{anaerobic}} - \text{R}_{\text{anaerobic}}$$

Table 7-16: Variables and Data Sources for CH_4 Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems (kt CH_4/year)			
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2020: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2020: Forecasted from the rest of the time series
$S_{anaerobic}$	Organic component removed from anaerobic wastewater treatment (0)	Gg/year	1990-2020: IPCC (2019)
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0.48)	kg CH_4/kg BOD	
$R_{anaerobic}$	Amount CH_4 recovered or flared from anaerobic wastewater treatment (0)	kg CH_4/year	

[a] Value of this activity data varies over the time series.

Emissions from Anaerobic Sludge Digesters:

Total CH_4 emissions from anaerobic sludge digesters were estimated by multiplying the wastewater influent flow to POTWs with anaerobic sludge digesters, the cubic feet of digester gas generated per person per day divided by the flow to POTWs, the fraction of CH_4 in biogas, the density of CH_4, one minus the destruction efficiency from burning the biogas in an energy/thermal device and then converting the results to kt/year.

Equation 7-15: Emissions from Anaerobic Sludge Digesters (U.S. Specific)

$$\text{D (kt CH}_4\text{/year)} = [(\text{POTW\_flow\_AD}) \times (\text{biogas gen})/(100)] \times 0.0283 \times (\text{FRAC\_CH}_4) \times 365.25 \times (662) \times (\text{1-DE}) \times 1/10^9$$

Table 7-17: Variables and Data Sources for Emissions from Anaerobic Sludge Digesters

Variable	Variable Description	Units	Inventory years: Source of Value
Emissions from Anaerobic Sludge Digesters (kt CH_4/year)			
POTW_flow_AD	POTW Flow to Facilities with Anaerobic Sludge Digesters[a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, and 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2020: Forecasted from the rest of the time series
biogas gen	Gas Generation Rate (1.0)	ft^3/capita/day	1990-2020: Metcalf & Eddy (2014)
100	Per Capita POTW Flow (100)	gal/capita/day	1990-2020: Ten-State Standards (2004)
0.0283	Conversion factor	ft^3 to m^3	Standard Conversion
FRAC_CH_4	Proportion of Methane in Biogas (0.65)	No units	1990-2020: Metcalf & Eddy (2014)
365.25	Conversion factor	Days in a year	Standard conversion
662	Density of Methane (662)	g CH_4/m^3 CH_4	1990-2020: EPA (1993a)

Variable	Variable Description	Units	Inventory years: Source of Value
DE	Destruction Efficiency (99% converted to fraction)	No units	1990-2020: EPA (1998b); CAR (2011); Sullivan (2007); Sullivan (2010); and UNFCCC (2012)
$1/10^9$	Conversion factor	g to kt	Standard conversion

[a] Value of this activity data varies over the time series.

Emissions from Discharge of Centralized Treatment Effluent:

Methane emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge. The BOD in treated effluent was determined by multiplying the total organics in centrally treated wastewater by the percent of wastewater treated in primary, secondary, and tertiary treatment, and the fraction of organics remaining after primary treatment (one minus the fraction of organics removed from primary treatment, secondary treatment, and tertiary treatment).

Equation 7-16: Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$E\ (\text{kt CH}_4/\text{year}) = (TOW_{RLE} \times EF_{RLE}) + (TOW_{Other} \times EF_{Other})$$

where,

Equation 7-17: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.3D])

$$TOW_{EFFtreat,CENTRALIZED}\ (\text{Gg BOD/year}) = [TOW_{CENTRALIZED} \times \%\ \text{primary} \times (1\text{-}TOW_{rem,PRIMARY})] + [TOW_{CENTRALIZED} \times \%\ \text{secondary} \times (1\text{-}TOW_{rem,SECONDARY})] + [TOW_{CENTRALIZED} \times \%\ \text{tertiary} \times (1\text{-}TOW_{rem,TERTIARY})]$$

Equation 7-18: Total Organics in Effluent Discharged to Reservoirs, Lakes, or Estuaries (U.S.-Specific)

$$TOW_{RLE}\ (\text{Gg BOD/year}) = TOW_{EFFtreat,CENTRALIZED} \times Percent_{RLE}$$

Equation 7-19: Total Organics in Effluent Discharged to Other Waterbodies (U.S.-Specific)

$$TOW_{Other}\ (\text{Gg BOD/year}) = TOW_{EFFtreat,CENTRALIZED} \times Percent_{Other}$$

Table 7-18: Variables and Data Sources for CH_4 Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$TOW_{EFFtreat,CENTRALIZED}$	Total organics in centralized treatment effluent[a]	Gg BOD/year	1990-2020: Calculated
$TOW_{CENTRALIZED}$	Total organics in centralized wastewater treatment[a]	Gg BOD/year	1990-2020: Calculated
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	

Variable	Variable Description	Units	Source of Value
			obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
$TOW_{rem,PRIMARY}$	Fraction of organics removed from primary domestic centralized treatment (0.4)	No units	1990-2020: IPCC (2019)
$TOW_{rem,SECONDARY}$	Fraction of organics removed from secondary domestic centralized treatment (0.85)	No units	
$TOW_{rem,TERTIARY}$	Fraction of organics removed from tertiary domestic centralized treatment (0.90)	No units	
TOW_{RLE}	Total organics in effluent discharged to reservoirs, lakes, and estuaries[a]	Gg BOD/year	1990-2020: Calculated
TOW_{Other}	Total organics in effluent discharge to other waterbodies[a]	Gg BOD/year	
EF_{RLE}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.021)	kg CH_4/kg BOD	1990-2020: IPCC (2019)
EF_{Other}	Emission factor (discharge to other waterbodies) (0.114)	kg CH_4/kg BOD	
$Percent_{RLE}$	% discharged to reservoirs, lakes, and estuaries[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a) 2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2020: Set equal to 2012
$Percent_{Other}$	% discharged to other waterbodies[a]	%	

[a] Value of this activity data varies over the time series.

Industrial Wastewater CH_4 Emission Estimates

Industrial wastewater CH_4 emissions originate from on-site treatment systems, typically comprised of biological treatment operations. The collection systems at an industrial plant are not as extensive as domestic wastewater sewer systems; therefore, it is not expected that dissolved CH_4 will form during collection. However, some treatment systems are designed to have anaerobic activity (e.g., anaerobic reactors or lagoons), or may periodically have anaerobic conditions form (facultative lagoons or large stabilization basins). Emissions will also result from discharge of treated effluent to waterbodies where carbon accumulates in sediments (typically slow-moving systems, such as lakes, reservoirs, and estuaries).

Industry categories that are likely to produce significant CH_4 emissions from wastewater treatment were identified and included in the Inventory. The main criteria used to identify U.S. industries likely to generate CH_4 are whether they generate high volumes of wastewater, whether there is a high organic wastewater load, and whether the wastewater is treated using methods that result in CH_4 emissions. The top six industries that meet these criteria are pulp and paper manufacturing; meat and poultry processing; vegetables, fruits, and juices processing; starch-based ethanol production; petroleum refining; and breweries. Wastewater treatment and discharge emissions for these sectors for 2020 are displayed in Table 7-19 below. Further discussion of wastewater treatment for each industry is included below.

Table 7-19: Total Industrial Wastewater CH_4 Emissions by Sector (2020, MMT CO_2 Eq. and Percent)

Industry	CH_4 Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater CH_4
Meat & Poultry	5.0	78.2
Pulp & Paper	0.8	12.2
Fruit & Vegetables	0.2	3.6
Ethanol Refineries	0.1	2.3
Breweries	0.1	2.1
Petroleum Refineries	0.1	1.5
Total	**6.4**	**100**

Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

Equation 7-20 presents the general IPCC equation (Equation 6.4, IPCC 2019) to estimate methane emissions from each type of treatment system used for each industrial category.

Equation 7-20: Total CH_4 Emissions from Industrial Wastewater

$$CH_4 \text{ (industrial sector)} = [(TOW_i - S_i) \times EF - R_i]$$

where,

CH_4 (industrial sector) = Total CH_4 emissions from industrial sector wastewater treatment (kg/year)
i = Industrial sector
TOW_i = Total organics in wastewater for industrial sector *i* (kg COD/year)
S_i = Organic component removed from aerobic wastewater treatment for industrial sector *i* (kg COD/year)
EF = System-specific emission factor (kg CH_4/kg COD)
R_i = Methane recovered for industrial sector I (kg CH_4/year)

Equation 7-21 presents the general IPCC equation to estimate the total organics in wastewater (TOW) for each industrial category.

Equation 7-21: TOW in Industry Wastewater Treatment Systems

$$TOW_i = P_i \times W_i \times COD_i$$

where,

TOW_i = Total organically degradable material in wastewater for industry I (kg COD/yr)
i = Industrial sector
P_i = Total industrial product for industrial sector *i* (t/yr)
W_i = Wastewater generated (m^3/t product)
COD_i = Chemical oxygen demand (industrial degradable organic component in wastewater) (kg COD/m^3)

The annual industry production is shown in Table 7-20, and the average wastewater outflow and the organics loading in the outflow is shown in Table 7-21. For some industries, U.S.-specific data on organics loading is reported as BOD rather than COD. In those cases, an industry-specific COD:BOD ratio is used to convert the organics loading to COD.

The amount of organics treated in each type of wastewater treatment system was determined using the percent of wastewater in the industry that is treated on site and whether the treatment system is anaerobic, aerobic or partially anaerobic. Table 7-22 presents the industrial wastewater treatment activity data used in the calculations and described in detail in ERG (2008a), ERG (2013a), ERG (2013b), and ERG (2021a). For CH_4 emissions, wastewater treated in anaerobic lagoons or reactors was categorized as “anaerobic”, wastewater treated in aerated stabilization basins or facultative lagoons were classified as “ASB” (meaning there may be pockets of anaerobic activity), and wastewater treated in aerobic systems such as activated sludge systems were classified as “aerobic/other.”

The amount of organic component removed from aerobic wastewater treatment as a result of sludge removal ($S_{aerobic}$) was either estimated as an industry-specific percent removal, if available, or as an estimate of sludge produced by the treatment system and IPCC default factors for the amount of organic component removed (K_{rem}), using one of the following equations. Table 7-23 presents the sludge variables used for industries with aerobic wastewater treatment operations (i.e., pulp and paper, fruit/vegetable processing, and petroleum refining).

Equation 7-22: Organic Component Removed from Aerobic Wastewater Treatment – Pulp, Paper, and Paperboard

$$S_{pulp,asb} = TOW_{pulp} \times \% \text{ removal w/primary}$$

where,

$S_{pulp,asb}$ = Organic component removed from pulp and paper wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
TOW_{pulp} = Total organically degradable material in pulp and paper wastewater (Gg COD/yr)
% removal w/primary = Percent reduction of organics in pulp and paper wastewater associated with sludge removal from primary treatment (%)

Equation 7-23: Organic Component Removed from Aerobic Treatment Plants

$$S_{aerobic} = S_{mass} \times K_{rem} \times 10^{-6}$$

where,

$S_{aerobic}$ = Organic component removed from fruit and vegetable or petroleum refining wastewater during primary treatment before treatment in aerated stabilization basins (Gg COD/yr)
S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
K_{rem} = Sludge factor (kg BOD/kg sludge)
10^{-6} = Conversion factor, kilograms to Gigagrams

Equation 7-24: Raw Sludge Removed from Wastewater Treatment as Dry Mass

$$S_{mass} = (S_{prim} + S_{aer}) \times P \times W$$

where,

S_{mass} = Raw sludge removed from wastewater treatment as dry mass (kg sludge/yr)
S_{prim} = Sludge production from primary sedimentation (kg sludge/m^3)
S_{aer} = Sludge production from secondary aerobic treatment (kg sludge/m^3)
P = Production (t/yr)
W = Wastewater Outflow (m^3/t)

Default emission factors[9] from IPCC (2019) were used. Information on methane recovery operations varied by industry. See industry descriptions below.

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[9] Emission factors are calculated by multiplying the maximum CH_4-producing capacity of wastewater (B_0, 0.25 kg CH_4/kg COD) and the appropriate methane correction factors (MCF) for aerobic (0), partially anaerobic (0.2), and anaerobic (0.8) systems (IPCC 2019).

Table 7-20: U.S. Pulp and Paper, Meat, Poultry, Vegetables, Fruits and Juices, Ethanol, Breweries, and Petroleum Refining Production (MMT)

Year	Pulp and Paper[a]	Meat (Live Weight Killed)	Poultry (Live Weight Killed)	Vegetables, Fruits and Juices	Ethanol Production	Breweries	Petroleum Refining
1990	83.6	27.3	14.6	38.7	2.5	23.9	702.4
2005	92.4	31.4	25.1	42.9	11.7	23.1	818.6
2016	79.9	34.2	28.3	43.5	45.8	22.3	926.0
2017	80.3	35.4	28.9	42.9	47.2	21.8	933.5
2018	78.7	36.4	29.4	42.4	48.1	21.5	951.7
2019	76.3	37.4	30.1	43.5	47.1	21.1	940.0
2020	76.1	37.8	30.5	43.5	41.6	21.1	806.7

[a] Pulp and paper production is the sum of market pulp production plus paper and paperboard production.

Sources: Pulp and Paper - FAO (2021a) and FAO (2021b); Meat, Poultry, and Vegetables - USDA (2021a and 2021c); Ethanol - Cooper (2018) and RFA (2021a and 2021b); Breweries - Beer Institute (2011) and TTB (2021); Petroleum Refining - EIA (2021).

Table 7-21: U.S. Industrial Wastewater Characteristics Data (2020)

Industry	Wastewater Outflow (m^3/ton)	Wastewater BOD (g/L)	Wastewater COD (kg/m^3)	COD:BOD Ratio
Pulp and Paper	See Table 7-25	0.3	--	2.5
Meat Processing	5.3	2.8	--	3
Poultry Processing	12.5	1.5	--	3
Fruit/Vegetable Processing	See Table 7-26		--	1.5
Ethanol Production – Wet Mill	10[a]	1.5	--	2
Ethanol Production – Dry Mill	1.25[a]	3[b]	--	2
Petroleum Refining	0.8	--	0.45	2.5
Breweries – Craft	3.09	--	17.6	1.67
Breweries – NonCraft	1.94	--	17.6	1.67

[a] Units are gallons per gallons ethanol produced.

[b] Units are COD (g/L).

Sources: Pulp and Paper (BOD, COD:BOD) - Malmberg (2018); Meat and Poultry (Outflow, BOD) - EPA (2002); Meat and Poultry (COD:BOD) - EPA (1997a); Fruit/Vegetables (Outflow, BOD) – CAST (1995), EPA (1974), EPA (1975); Fruit/Vegetables (COD:BOD) - EPA (1997a); Ethanol Production – Wet Mill (Outflow) - Donovan (1996), NRBP (2001), Ruocco (2006a); Ethanol Production – Wet Mill (BOD) - White and Johnson (2003); Ethanol Production – Dry Mill (Outflow and COD) - Merrick (1998), Ruocco (2006a); Ethanol Production (Dry and Wet, COD:BOD) - EPA (1997a); Petroleum Refining (Outflow) - ERG (2013b); Petroleum Refining (COD) - Benyahia et al. (2006); Petroleum Refining (COD:BOD) – EPA (1982); Breweries – Craft BIER (2017); ERG (2018b); Breweries – NonCraft ERG (2018b); Brewers Association (2016a); Breweries (Craft and NonCraft; COD and COD:BOD) - Brewers Association (2016b).

Table 7-22: U.S. Industrial Wastewater Treatment Activity Data

Industry	% Wastewater Treated On Site	% Treated Anaerobically	% Treated Aerobically	% Treated Aerobically: % Treated in ASBs	% Treated Aerobically: % Treated in Other Aerobic
Pulp and Paper	60	5.2	75.9	38.5	37.4
Meat Processing	33	33[a]	33	0	33
Poultry Processing	25	25[a]	25	0	25
Fruit/Vegetable Processing	11	0	11	5.5	5.5
Ethanol Production – Wet Mill	33.3	33.3	0	0	0
Ethanol Production – Dry Mill	75	75	0	0	0
Petroleum Refining	62.1	0	62.1	23.6	38.5
Breweries – Craft	0.5	0.5	0	0	0
Breweries - NonCraft	100	99	1	0	1

[a] Wastewater is pretreated in anaerobic lagoons prior to aerobic treatment.

Note: Due to differences in data availability and methodology, zero values in the table are for calculation purposes only and may indicate unavailable data.

Sources: ERG (2008b); ERG (2013a); ERG (2013b); ERG (2021a).

Table 7-23: Sludge Variables for Aerobic Treatment Systems

Variable	Industry: Pulp and Paper	Industry: Fruit/Vegetable Processing	Industry: Petroleum Refining
Organic reduction associated with sludge removal (%)	58		
Sludge Production (kg/m^3)			
Primary Sedimentation		0.15	
Aerobic Treatment		0.096	0.096
Sludge Factor (kg BOD/kg dry mass sludge)			
Aerobic Treatment w/Primary Sedimentation and No Anaerobic Sludge Digestion		0.8	
Aerobic Treatment w/out Primary Sedimentation			1.16

Sources: Organic reduction (pulp) – ERG (2008a); Sludge production - Metcalf & Eddy (2003); Sludge factors – IPCC (2019).

Emissions from Discharge of Industrial Wastewater Treatment Effluent:

Methane emissions from discharge of industrial wastewater treatment effluent are estimated via a Tier 1 method for all industries except for pulp, paper, and paperboard. Emissions from discharge of pulp, paper, and paperboard treatment effluent is estimated via a Tier 2 method and is described in the industry-specific data section. Tier 1 emissions from effluent are estimated by multiplying the total organic content of the discharged wastewater effluent by an emission factor associated with the discharge:

Equation 7-25: CH_4 Emissions from Industrial Wastewater Treatment Discharge

$$\mathrm{CH_4\ Effluent_{IND}} = \mathrm{TOW_{EFFLUENT,IND}} \times \mathrm{EF_{EFFLUENT}}$$

where,

$\mathrm{CH_4\ Effluent_{IND}}$ = CH_4 emissions from industrial wastewater discharge for inventory year (kg CH_4/year)
$\mathrm{TOW_{EFFLUENT,IND}}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
$\mathrm{EF_{EFFLUENT}}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.028 kg CH_4/kg COD or 0.068 kg CH_4/kg BOD) (IPCC 2019)

The COD or BOD in industrial treated effluent ($\mathrm{TOW_{EFFLUENT,IND}}$) was determined by multiplying the total organics in the industry's untreated wastewater that is treated on site by an industry-specific percent removal where available or a more general percent removal based on biological treatment for other industries. Table 7-22 presents the percent of wastewater treated onsite, while Table 7-24 presents the fraction of TOW removed during treatment.

Equation 7-26: TOW in Industrial Wastewater Effluent

$$TOW_{EFFLUENT,IND} = TOW_{IND} * \%onsite * (1 - TOW_{REM})$$

where,

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in wastewater effluent from industry for inventory year (kg COD/year or kg BOD/year)
TOW_{IND} = Total organics in untreated wastewater for industry (kg COD/year)
%onsite = Percent of industry wastewater treated on site (%)
TOW_{REM} = Fraction of organics removed during treatment

Table 7-24: Fraction of TOW Removed During Treatment by Industry

Industry	TOW_{REM}	Source
Pulp, Paper, and Paperboard	0.905	Malmberg (2018)
Red Meat and Poultry	0.85	IPCC (2019), Table 6.6b
Fruits and Vegetables	0.85	IPCC (2019), Table 6.6b
Ethanol Production		
Biomethanator Treatment	0.90	ERG (2008a), ERG (2006b)
Other Treatment	0.85	IPCC (2019), Table 6.6b
Petroleum Refining	0.93	Kenari, Sarrafzadeh, and Tavakoli (2010)
Breweries	0.85	IPCC (2019), Table 6.6b

Discussion of Industry-Specific Data:

Pulp, Paper, and Paperboard manufacturing Wastewater Treatment. Wastewater treatment for the pulp, paper, and paperboard manufacturing (hereinafter referred to as “pulp and paper”) industry typically includes neutralization, screening, sedimentation, and flotation/hydrocycloning to remove solids (World Bank 1999; Nemerow and Dasgupta 1991). Secondary treatment (storage, settling, and biological treatment) mainly consists of lagooning. About 60 percent of pulp and paper mills have on-site treatment with primary treatment and about half of these also have secondary treatment (ERG 2008). In the United States, primary treatment is focused on solids removal, equalization, neutralization, and color reduction (EPA 1993b). The vast majority of pulp and paper mills with on-site treatment systems use mechanical clarifiers to remove suspended solids from the wastewater. About 10 percent of pulp and paper mills with treatment systems use settling ponds for primary treatment and these are more likely to be located at mills that do not perform secondary treatment (EPA 1993b).

Approximately 42 percent of the BOD passes on to secondary treatment, which consists of activated sludge, aerated stabilization basins, or non-aerated stabilization basins. Pulp and paper mill wastewater treated using anaerobic ponds or lagoons or unaerated ponds were classified as anaerobic (with an MCF of 0.8). Wastewater flow treated in systems with aerated stabilization basins or facultative lagoons was classified as partially anaerobic (with an MCF of 0.2, which is the *2006 IPCC Guidelines*-suggested MCF for shallow lagoons). Wastewater flow treated in systems with activated sludge systems or similarly aerated biological systems was classified as aerobic.

A time series of CH_4 emissions for 1990 through 2019 was developed based on paper and paperboard production data and market pulp production data. Market pulp production values were available directly for 1998, 2000 through 2003, and 2010 through 2018. Where market pulp data were unavailable, a percent of woodpulp that is market pulp was applied to woodpulp production values from FAOSTAT to estimate market pulp production (FAO 2020a). The percent of woodpulp that is market pulp for 1990 to 1997 was assumed to be the same as 1998, 1999 was interpolated between values for 1998 and 2000, 2000 through 2009 were interpolated between values for 2003 and 2010, and 2019 was forecasted from the rest of the time series. A time series of the overall wastewater outflow is presented in Table 7-25. Data for 1990 through 1994 varies based on data outlined in ERG (2013a) to reflect historical wastewater flow. Wastewater generation rates for 1995, 2000, and 2002 were estimated from the 2014 *American Forest and Paper Association* (AF&PA) *Sustainability Report* (AF&PA 2014). Wastewater generation rates for 2004, 2006, 2008, 2010, 2012, and 2014 were estimated from the 2016 AF&PA Sustainability Report (AF&PA 2016). Data for 2005 and 2016 were obtained from the 2018 AF&PA Sustainability Report (AF&PA 2018), while data for 2018 were obtained from the 2020 AF&PA Sustainability Report (AF&PA 2020). Data for intervening years were obtained by linear interpolation, while 2019 to 2020 were set equal to 2018. The average BOD concentration in raw wastewater was estimated to be 0.4 grams BOD/liter for 1990 to 1998, while 0.3 grams BOD/liter was estimated for 2014 through 2020 (EPA 1997b; EPA 1993b; World Bank 1999; Malmberg 2018). Data for intervening years were obtained by linear interpolation.

Table 7-25: Wastewater Outflow (m^3/ton) for Pulp, Paper, and Paperboard Mills

Year	Wastewater Outflow (m^3/ton)
1990	68
2005	43
2016	40
2017	39
2018	40
2019	40
2020	40

Sources: ERG (2013a), AF&PA (2014), AF&PA (2016), AF&PA (2018), AF&PA (2020).

Pulp, Paper, and Paperboard Wastewater Treatment Effluent. Methane emissions from pulp, paper, and paperboard wastewater treatment effluent were estimated by multiplying the total BOD of the discharged wastewater effluent by an emission factor associated with the location of the discharge.

Equation 7-27: Emissions from Pulp and Paper Discharge (U.S. Specific)

$$\begin{gathered}\textit{Emissions from Pulp and Paper Discharge}\ (\text{U.S. Specific, kt CH}_4\text{/year})\\ = (TOW_{RLE,pulp} \times EF_{RLE}) + (TOW_{Other,pulp} \times EF_{Other})\end{gathered}$$

Equation 7-28: Total Organics in Pulp and Paper Effluent Discharged to Reservoirs, Lakes, Or Estuaries (U.S. Specific)

$$\begin{gathered}TOW_{RLE,pulp}\ (\text{Gg BOD/year})\\ = TOW_{EFFLUENT,IND} \times Percent_{RLE,pulp}\end{gathered}$$

Equation 7-29: Total Organics in Pulp and Paper Effluent Discharged to Other Waterbodies (U.S. Specific)

$$\begin{gathered}TOW_{Other,pulp}\ (\text{Gg BOD/year})\\ = TOW_{EFFLUENT,IND} \times Percent_{Other,pulp}\end{gathered}$$

where,

$TOW_{RLE,pulp}$ = Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to reservoirs, lakes, or estuaries (Gg BOD/year)

EF_{RLE} = Emission factor (discharge to reservoirs/lakes/estuaries) (0.114 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{Other,pulp}$ = Total organics in pulp, paper, and paperboard manufacturing wastewater treatment effluent discharged to other waterbodies (Gg BOD/year)

EF_{Other} = Emission factor (discharge to other waterbodies) (0.021 kg CH_4/kg BOD) (IPCC 2019)

$TOW_{EFFLUENT,IND}$ = Total organically degradable material in pulp, paper, and paperboard manufacturing wastewater effluent for inventory year (Gg BOD/year)

$Percent_{RLE,pulp}$ = Percent of wastewater effluent discharged to reservoirs, lakes, and estuaries (ERG 2021b)

$Percent_{Other,pulp}$ = Percent of wastewater effluent discharged to other waterbodies (ERG 2021b)

The percent of pulp, paper, and paperboard wastewater treatment effluent routed to reservoirs, lakes, or estuaries (3 percent) and other waterbodies (97 percent) were obtained from discussions with NCASI (ERG 2021b). Data for 2019 were assumed the same as the rest of the time series due to lack of available data. Default emission factors for reservoirs, lakes, and estuaries (0.114 kg CH_4/kg BOD) and other waterbodies (0.021 kg CH_4/kg BOD) were obtained from IPCC (2019).

Meat and Poultry Processing. The meat and poultry processing industry makes extensive use of anaerobic lagoons in sequence with screening, fat traps, and dissolved air flotation when treating wastewater on site. Although all meat and poultry processing facilities conduct some sort of treatment on site, about 33 percent of meat processing operations (EPA 2002) and 25 percent of poultry processing operations (U.S. Poultry 2006) perform on-site treatment in anaerobic lagoons. The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic lagoons were used to estimate the CH_4 produced from these on-site treatment systems.

Vegetables, Fruits, and Juices Processing. Treatment of wastewater from fruits, vegetables, and juices processing includes screening, coagulation/settling, and biological treatment (lagooning). The flows are frequently seasonal, and robust treatment systems are preferred for on-site treatment. About half of the operations that treat and discharge wastewater use lagoons intended for aerobic operation, but the large seasonal loadings may develop limited anaerobic zones. In addition, some anaerobic lagoons may also be used (Nemerow and Dasgupta 1991). Wastewater treated in partially anaerobic systems were assigned the IPCC default emission factor of 0.12 kg CH_4/kg BOD. Outflow and BOD data, presented in Table 7-26, were obtained from CAST (1995) for apples, apricots, asparagus, broccoli, carrots, cauliflower, cucumbers (for pickles), green peas, pineapples, snap beans, and spinach; EPA (1974) for potato and citrus fruit processing; and EPA (1975) for all other commodities.

Table 7-26: Wastewater Outflow (m^3/ton) and BOD Production (g/L) for U.S. Vegetables, Fruits, and Juices Production

Commodity	Wastewater Outflow (m^3/ton)	Organic Content in Untreated Wastewater (g BOD/L)
Vegetables		
Potatoes	10.27	1.765
Other Vegetables	9.88	0.752
Fruit		
Apples	9.08	8.16
Citrus Fruits	10.11	0.317
Non-citrus Fruits	12.59	1.226
Grapes (for wine)	2.78	1.831

Sources: CAST (1995); EPA (1974); EPA (1975).

Ethanol Production. Ethanol, or ethyl alcohol, is produced primarily for use as a fuel component, but is also used in industrial applications and in the manufacture of beverage alcohol. Ethanol can be produced from the fermentation of sugar-based feedstocks (e.g., molasses and beets), starch- or grain-based feedstocks (e.g., corn, sorghum, and beverage waste), and cellulosic biomass feedstocks (e.g., agricultural wastes, wood, and bagasse). Ethanol can also be produced synthetically from ethylene or hydrogen and carbon monoxide. However, synthetic ethanol comprises a very small percent of ethanol production in the United States. Currently, ethanol is mostly made from sugar and starch crops, but with advances in technology, cellulosic biomass is increasingly used as ethanol feedstock (DOE 2013).

Ethanol is produced from corn (or other sugar or starch-based feedstocks) primarily by two methods: wet milling and dry milling. Historically, the majority of ethanol was produced by the wet milling process, but now the majority is produced by the dry milling process. The dry milling process is cheaper to implement and is more efficient in terms of actual ethanol production (Rendleman and Shapouri 2007). The wastewater generated at ethanol production facilities is handled in a variety of ways. Dry milling facilities often combine the resulting evaporator condensate with other process wastewaters, such as equipment wash water, scrubber water, and boiler blowdown and anaerobically treat this wastewater using various types of digesters. Wet milling facilities often treat their steepwater condensate in anaerobic systems followed by aerobic polishing systems. Wet milling facilities may treat the stillage (or processed stillage) from the ethanol fermentation/distillation process separately or together with steepwater and/or wash water. Methane generated in anaerobic sludge digesters is commonly collected and either flared or used as fuel in the ethanol production process (ERG 2006b).

About 33 percent of wet milling facilities and 75 percent of dry milling facilities treat their wastewater anaerobically. A default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment was used to estimate the CH_4 produced from these on-site treatment systems. The amount of CH_4 recovered through the use of biomethanators was estimated, and a 99 percent destruction efficiency was used. Biomethanators are anaerobic reactors that use microorganisms under anaerobic conditions to reduce COD and organic acids and recover biogas from wastewater (ERG 2006b). For facilities using biomethanators, approximately 90 percent of BOD is removed during on-site treatment (ERG 2006b, 2008). For all other facilities, the removal of organics was assumed to be equivalent to secondary treatment systems, or 85 percent (IPCC 2019).

Petroleum Refining. Petroleum refining wastewater treatment operations have the potential to produce CH_4 emissions from anaerobic wastewater treatment. EPA's Office of Air and Radiation performed an Information Collection Request (ICR) for petroleum refineries in 2011.[10] Facilities that reported using non-aerated surface impoundments or other biological treatment units (trickling filter, rotating biological contactor), which have the potential to lead to anaerobic conditions, were assigned the IPCC default emission factor of 0.05 kg CH_4/kg COD. In addition, the wastewater generation rate was determined to be 26.4 gallons per barrel of finished product, or 0.8 m^3/ton (ERG 2013b).

Breweries. Since 2010, the number of breweries has increased from less than 2,000 to more than 8,000 (Brewers Association 2021). This increase has primarily been driven by craft breweries, which have increased by over 250 percent during that period. Craft breweries were defined as breweries producing less than six million barrels of beer per year, and non-craft breweries produce greater than six million barrels. With their large amount of water use and high strength wastewater, breweries generate considerable CH_4 emissions from anaerobic wastewater treatment. However, because many breweries recover their CH_4, their emissions are much lower.

The Alcohol and Tobacco Tax and Trade Bureau (TTB) provides total beer production in barrels per year for different facility size categories from 2007 to the present (TTB 2021). For years prior to 2007 where TTB data were not readily available, the Brewers Almanac (Beer Institute 2011) was used, along with an estimated percent of craft and non-craft breweries based on the breakdown of craft and non-craft for the years 2007 through 2020.

To determine the overall amount of wastewater produced, data on water use per unit of production and a wastewater-to-water ratio were used from the Benchmarking Report (Brewers Association 2016a) for both craft and non-craft breweries. Since brewing is a batch process, and different operations have varying organic loads, full-strength brewery wastewater can vary widely on a day-to-day basis. However, the organic content of brewery wastewater does not substantially change between craft and non-craft breweries. Some breweries may collect and discharge high strength wastewater from particular brewing processes (known as "side streaming") to a POTW, greatly reducing the organics content of the wastewater that is treated on site. Subsequently, the MCF for discharge to a POTW was assumed to be zero (ERG 2018b).

Breweries may treat some or all of their wastewater on site prior to discharge to a POTW or receiving water. On-site treatment operations can include physical treatment (e.g., screening, settling) which are not expected to

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[10] Available online at https://www.epa.gov/stationary-sources-air-pollution/comprehensive-data-collected-petroleum-refining-sector.

contribute to CH_4 emissions, or biological treatment, which may include aerobic treatment or pretreatment in anaerobic reactors (ERG 2018b). The IPCC default emission factor of 0.2 kg CH_4/kg COD for anaerobic treatment and 0 for aerobic treatment were used to estimate the CH_4 produced from these on-site treatment systems (IPCC 2006). The amount of CH_4 recovered through anaerobic wastewater treatment was estimated, and a 99 percent destruction efficiency was used (ERG 2018b; Stier J. 2018). Very limited activity data are available on the number of U.S. breweries that are performing side streaming or pretreatment of wastewater prior to discharge.

Domestic Wastewater N_2O Emission Estimates

Domestic wastewater N_2O emissions originate from both septic systems and POTWs. Within these centralized systems, N_2O emissions can result from aerobic systems, including systems like constructed wetlands. Emissions will also result from discharge of centrally treated wastewater to waterbodies with nutrient-impacted/eutrophic conditions. The systems with emission estimates are:

- Septic systems (A);
- Centralized treatment aerobic systems (B), including aerobic systems (other than constructed wetlands) (B1), constructed wetlands only (B2), and constructed wetlands used as tertiary treatment (B3);
- Centralized anaerobic systems (C); and
- Centralized wastewater treatment effluent (D).

Methodological equations for each of these systems are presented in the subsequent subsections; total domestic N_2O emissions are estimated as follows:

Equation 7-30: Total Domestic N_2O Emissions from Wastewater Treatment and Discharge

$$\text{Total Domestic N}_2\text{O Emissions from Wastewater Treatment and Discharge (kt)} = \text{A} + \text{B} + \text{C} + \text{D}$$

Table 7-27 presents domestic wastewater N_2O emissions for both septic and centralized systems, including emissions from centralized wastewater treatment effluent, in 2020.

Table 7-27: Domestic Wastewater N_2O Emissions from Septic and Centralized Systems (2020, kt, MMT CO_2 Eq. and Percent)

	N_2O Emissions (kt)	N_2O Emissions (MMT CO_2 Eq.)	% of Domestic Wastewater N_2O
Septic Systems	3	0.9	3.8
Centrally-Treated Aerobic Systems	58	17.2	74.8
Centrally-Treated Anaerobic Systems	0	0.0	0
Centrally-Treated Wastewater Effluent	16	4.9	21.3
Total	**77**	**23.0**	**100**

Note: Totals may not sum due to independent rounding.

Emissions from Septic Systems:

Nitrous oxide emissions from domestic treatment depend on the nitrogen present, in this case, in the form of protein. Per capita protein consumption (kg protein/person/year) was determined by multiplying per capita annual food availability data and its protein content. Those data are then adjusted using a factor to account for the fraction of protein actually consumed. The methodological equations are:

Equation 7-31: Annual per Capita Protein Supply (U.S. Specific)

$$\text{Protein}_{\text{SUPPLY}}\ (\text{kg/person/year}) = \text{Protein}_{\text{per capita}}/1000 \times 365.25$$

Equation 7-32: Consumed Protein [IPCC 2019 (Eq. 6.10A)]

$$\text{Protein (kg/person/year)}$$

$$= \text{Protein}_{\text{SUPPLY}} \times \text{FPC}$$

Table 7-28: Variables and Data Sources for Protein Consumed

Variable	Variable Description	Units	Inventory Years: Source of Value
Protein			
$\text{Protein}_{\text{SUPPLY}}$	Annual per capita protein supply[a]	kg/person/year	1990-2020: Calculated
$\text{Protein}_{\text{per capita}}$	Daily per capita protein supply[a]	g/person/day	1990-2020: USDA (2021b)
1000	Conversion factor	g to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion
FPC	Fraction of Protein Consumed[a]	kg protein consumed / kg protein available	1990-2010: USDA (2021b) 2011-2018: FAO (2021c) and scaling factor 2019, 2020: Forecasted from the rest of the time series

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from septic systems were estimated by multiplying the U.S. population by the percent of wastewater treated in septic systems (about 17 percent in 2020; U.S. Census Bureau 2019), consumed protein per capita (kg protein/person/year), the fraction of N in protein, the correction factor for additional nitrogen from household products, the factor for industrial and commercial co-discharged protein into septic systems, the factor for non-consumed protein added to wastewater and an emission factor and then converting the result to kt/year. All factors obtained from IPCC (2019).

U.S. population data were taken from the U.S. Census Bureau International Database (U.S. Census Bureau 2021) and include the populations of the United States, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. The fraction of the U.S. population using septic systems, as well as centralized treatment systems (see below), is based on data from *American Housing Survey* (U.S. Census Bureau 2019). The methodological equations are:

Equation 7-33: Total Nitrogen Entering Septic Systems (IPCC 2019 [Eq. 10])

$$\text{TN}_{\text{DOM\_SEPTIC}}\ (\text{kg N/year}) \\ = (\text{US}_{\text{POP}} \times \text{T}_{\text{SEPTIC}}) \times \text{Protein} \times \text{F}_{\text{NPR}} \times \text{N}_{\text{HH}} \times \text{F}_{\text{NON-CON\_septic}} \times \text{F}_{\text{IND-COM\_septic}}$$

Equation 7-34: Emissions from Septic Systems (IPCC 2019 [Eq. 6.9])

$$\text{A}\ (\text{kt N}_2\text{O/year}) \\ = \text{TN}_{\text{DOM\_SEPTIC}} \times (\text{EF}_{\text{SEPTIC}}) \times 44/28 \times 1/10^6$$

Table 7-29: Variables and Data Sources for N_2O Emissions from Septic System

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Septic Systems			
$\text{TN}_{\text{DOM\_SEPTIC}}$	Total nitrogen entering septic systems	kg N/year	1990-2020: Calculated
US_{POP}	U.S. population[a]	Persons	1990-2020: U.S. Census Bureau (2021)
T_{SEPTIC}	Percent treated in septic systems[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020: Forecasted from the rest of the time series
F_{NPR}	Fraction of nitrogen in protein (0.016)	kg N/kg protein	1990-2020: IPCC (2019)

Variable	Variable Description	Units	Inventory Years: Source of Value
N_{HH}	Additional nitrogen from household products (1.17)	No units	
$F_{IND\text{-}COM\_septic}$	Factor for Industrial and Commercial Co-Discharged Protein, septic systems (1)	No units	
$F_{NON\text{-}CON\_septic}$	Factor for Non-Consumed Protein Added to Wastewater (1.13)	No units	
EF_{SEPTIC}	Emission factor, septic systems (0.0045)	kg N_2O-N/kg N	
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Emissions from Centrally Treated Aerobic and Anaerobic Systems:

Nitrous oxide emissions from POTWs depend on the total nitrogen entering centralized wastewater treatment. The total nitrogen entering centralized wastewater treatment was estimated by multiplying the U.S. population by the percent of wastewater collected for centralized treatment (about 83 percent in 2020), the consumed protein per capita, the fraction of N in protein, the correction factor for additional N from household products, the factor for industrial and commercial co-discharged protein into wastewater treatment, and the factor for non-consumed protein added to wastewater.

Equation 7-35: Total Nitrogen Entering Centralized Systems (IPCC 2019 [Eq. 10])

$$TN_{DOM\_CENTRAL}\ (\text{kg N/year}) = (US_{POP} \times T_{CENTRALIZED}) \times \text{Protein} \times F_{NPR} \times N_{HH} \times F_{NON\text{-}CON} \times F_{IND\text{-}COM}$$

Table 7-30: Variables and Data Sources for Non-Consumed Protein and Nitrogen Entering Centralized Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
US_{POP}	U.S. population[a]	Persons	1990-2020: U.S. Census Bureau (2021)
$T_{CENTRALIZED}$	Percent collected[a]	%	Odd years from 1989 through 2019: U.S. Census Bureau (2019) Data for intervening years obtained by linear interpolation 2020: Forecasted from the rest of the time series
Protein	Consumed protein per capita[a]	kg/person/year	1990-2020: Calculated
F_{NPR}	Fraction of nitrogen in protein (0.16)	kg N/kg protein	1990-2020: IPCC (2019)
N_{HH}	Factor for additional nitrogen from household products (1.17)	No units	1990-2020: IPCC (2019)
$F_{NON\text{-}CON}$	Factor for U.S. specific non-consumed protein (1.13)	No units	
$F_{IND\text{-}COM}$	Factor for Industrial and Commercial Co-Discharged Protein (1.25)	No units	

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from POTWs were estimated by multiplying the total nitrogen entering centralized wastewater treatment, the relative percentage of wastewater treated by aerobic systems (other than constructed wetlands) and anaerobic systems, aerobic systems with constructed wetlands as the sole treatment, the emission factor for aerobic systems and anaerobic systems, and the conversion from N_2 to N_2O.

Table 7-34 presents the data for U.S. population, population served by centralized wastewater treatment plants, available protein, and protein consumed. The methodological equations are:

Equation 7-36: Total Domestic N_2O Emissions from Centrally Treated Aerobic Systems

$$\textit{Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands)}\ (\mathrm{B1}) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only)}\ (\mathrm{B2}) + \textit{Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment)}\ (\mathrm{B3}) = \mathrm{B}\ (\mathrm{kt}\ N_2O/\mathrm{year})$$

where,

Equation 7-37: Emissions from Centrally Treated Aerobic Systems (other than Constructed Wetlands) (IPCC 2019 [Eq. 6.9])

$$\mathrm{B1}\ (\mathrm{kt}\ N_2O/\mathrm{year}) = [(\mathrm{TN}_{\mathrm{DOM\_CENTRAL}}) \times (\%\ \mathrm{aerobic}_{\mathrm{OTCW}})] \times \mathrm{EF}_{\mathrm{aerobic}} \times 44/28 \times 1/10^6$$

Table 7-31: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Aerobic Systems (Other than Constructed Wetlands) (kt N_2O/year)			
$\mathrm{TN}_{\mathrm{DOM\_CENTRAL}}$	Total nitrogen entering centralized systems[a]	kg N/year	1990-2020: Calculated
% $\mathrm{aerobic}_{\mathrm{OTCW}}$	Flow to aerobic systems, other than constructed wetlands only / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: EPA (1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2020: Forecasted from the rest of the time series
$\mathrm{EF}_{\mathrm{aerobic}}$	Emission factor – aerobic systems (0.015)	kg N_2O-N/kg N	1990-2020: ERG (2021b)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Nitrous oxide emissions from constructed wetlands used as sole treatment include similar data and processes as aerobic systems other than constructed wetlands. See description above. Nitrous oxide emissions from constructed wetlands used as tertiary treatment were estimated by multiplying the flow to constructed wetlands used as tertiary treatment, wastewater N concentration entering tertiary treatment, constructed wetlands emission factor, and converting to kt/year.

Equation 7-38: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands Only) (IPCC 2014 [Eq. 6.9])

$$\mathrm{B2}\ (\mathrm{kt}\ N_2O/\mathrm{year}) = [(\mathrm{TN}_{\mathrm{DOM\_CENTRAL}}) \times (\%\mathrm{aerobic}_{\mathrm{CW}})] \times \mathrm{EF}_{\mathrm{CW}} \times 44/28 \times 1/10^6$$

Equation 7-39: Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands used as Tertiary Treatment) (U.S.-Specific)

$$\mathrm{B3}\ (\mathrm{kt}\ N_2O/\mathrm{year}) = [(\mathrm{POTW\_flow\_CW}) \times (\mathrm{N}_{\mathrm{CW,INF}}) \times 3.785 \times (\mathrm{EF}_{\mathrm{CW}})] \times 1/10^6 \times 365.25$$

Table 7-32: Variables and Data Sources for N_2O Emissions from Centrally Treated Aerobic Systems (Constructed Wetlands)

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Constructed Wetlands Only (kt N_2O/year)			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2020: Calculated
% $aerobic_{CW}$	Flow to aerobic systems, constructed wetlands used as sole treatment / total flow to POTWs[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2020: IPCC (2014)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
Emissions from Constructed Wetlands used as Tertiary Treatment (kt N_2O/year)			
POTW_flow_CW	Wastewater flow to POTWs that use constructed wetlands as tertiary treatment [a]	MGD	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008b, and 2012) Data for intervening years obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
$N_{CW,INF}$	BOD concentration in wastewater entering the constructed wetland (25)	mg/L	1990-2020: Metcalf & Eddy (2014)
3.785	Conversion factor	liters to gallons	Standard conversion
EF_{CW}	Emission factor for constructed wetlands (0.0013)	kg N_2O-N/kg N	1990-2020: IPCC (2014)
$1/10^6$	Conversion factor	mg to kg	Standard conversion
365.25	Conversion factor	Days in a year	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Data sources and methodologies are similar to those described for aerobic systems, other than constructed wetlands. See discussion above.

Equation 7-40: Emissions from Centrally Treated Anaerobic Systems (IPCC 2019 [Eq. 6.9])

$$C\ (\text{kt } N_2O/\text{year}) = [(TN_{DOM\_CENTRAL}) \times (\%\ \text{anaerobic})] \times EF_{anaerobic} \times 44/28 \times 1/10^6$$

Table 7-33: Variables and Data Sources for N_2O Emissions from Centrally Treated Anaerobic Systems

Variable	Variable Description	Units	Inventory Years: Source of Value
Emissions from Centrally Treated Anaerobic Systems			
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2020: Calculated
% anaerobic	Percent centralized wastewater that is anaerobically treated[a]	%	1990, 1991: Set equal to 1992 1992, 1996, 2000, 2004: (EPA 1992, 1996, 2000, 2004a), respectively Data for intervening years obtained by linear interpolation. 2005-2020: Forecasted from the rest of the time series
$EF_{anaerobic}$	Emission factor for anaerobic reactors/deep lagoons (0)	kg N_2O-N/kg N	1990-2020: IPCC (2019)
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	mg to kg	Standard conversion

[a] Value of this activity data varies over the Inventory time series.

Table 7-34: U.S. Population (Millions) Fraction of Population Served by Centralized Wastewater Treatment (percent), Protein Supply (kg/person-year), and Protein Consumed (kg/person-year)

Year	Population	Centralized WWT Population (%)	Protein Supply	Protein Consumed
1990	253	75.6	43.1	33.2
2005	300	78.8	44.9	34.7
2016	327	81.1	44.5	34.3
2017	329	82.1	44.7	34.5
2018	330	82.9	44.9	34.7
2019	332	83.6	44.4	34.2
2020	336	82.7	44.4	34.2

Sources: Population - U.S. Census Bureau (2021); WWTP Population - U.S. Census Bureau (2019); Available Protein - USDA (2021b); Protein Consumed - FAO (2021c).

Emissions from Discharge of Centralized Treatment Effluent:

Nitrous oxide emissions from the discharge of wastewater treatment effluent were estimated by multiplying the total nitrogen in centrally treated wastewater effluent by the percent of wastewater treated in primary, secondary, and tertiary treatment and the fraction of nitrogen remaining after primary, secondary, or tertiary treatment and then multiplying by the percent of wastewater volume routed to waterbodies with nutrient-impaired/eutrophic conditions and all other waterbodies (ERG 2021a) and emission factors for discharge to impaired waterbodies and other waterbodies from IPCC (2019). The methodological equations are:

Equation 7-41: Emissions from Centrally Treated Systems Discharge (U.S.-Specific)

$$\mathrm{D\ (kt\ N_2O/year)} \\ = [(\mathrm{N_{EFFLUENT,IMP}} \times \mathrm{EF_{IMP}}) + (\mathrm{N_{EFFLUENT,NONIMP}} \times \mathrm{EF_{NONIMP}})] \times 44/28 \times 1/10^6$$

where,

Equation 7-42: Total Organics in Centralized Treatment Effluent (IPCC 2019 [Eq. 6.8])

$$\mathrm{N_{EFFULENT,DOM}\ (kg\ N/year)}$$

$$= [\mathrm{TN}_{\mathrm{DOM\_CENTRAL}}\text{[11]} \times \%\ \mathrm{primary} \times (1\text{-}N_{\mathrm{rem,PRIMARY}})] + [\mathrm{TN}_{\mathrm{DOM\_CENTRAL}} \times \%\ \mathrm{secondary} \times (1\text{-}N_{\mathrm{rem,SECONDARY}})] + [\mathrm{TN}_{\mathrm{DOM\_CENTRAL}} \times \%\ \mathrm{tertiary} \times (1\text{-}N_{\mathrm{rem,TERTIARY}})]$$

Equation 7-43: Total Nitrogen in Effluent Discharged to Impaired Waterbodies (U.S.-Specific)

$$N_{\mathrm{EFFLUENT,IMP}}\ (\mathrm{kg\ N/year}) = (N_{\mathrm{EFFULENT,DOM}} \times \mathrm{Percent}_{\mathrm{IMP}})/1000$$

Equation 7-44: Total Nitrogen in Effluent Discharged to Nonimpaired Waterbodies (U.S.-Specific)

$$N_{\mathrm{EFFLUENT,NONIMP}}\ (\mathrm{kg\ N\ year}) = (N_{\mathrm{EFFLUENT,DOM}} \times \mathrm{Percent}_{\mathrm{NONIMP}})/1000$$

Table 7-35: Variables and Data Sources for N_2O Emissions from Centrally Treated Systems Discharge

Variable	Variable Description	Units	Source of Value
$N_{EFFULENT,DOM}$	Total organics in centralized treatment effluent[a]	kg N/year	1990-2020: Calculated
44/28	Conversion factor	Molecular weight ratio of N_2O to N_2	Standard conversion
$1/10^6$	Conversion factor	kg to kt	Standard conversion
$TN_{DOM\_CENTRAL}$	Total nitrogen entering centralized treatment[a]	kg N/year	1990-2020: Calculated
1000	Conversion factor	kg to kt	Standard Conversion
% primary	Percent of primary domestic centralized treatment[a]	%	1990,1991: Set equal to 1992. 1992, 1996, 2000, 2004, 2008, 2012: EPA (1992, 1996, 2000, 2004a, 2008, and 2012), respectively Data for intervening years obtained by linear interpolation. 2013-2020: Forecasted from the rest of the time series
% secondary	Percent of secondary domestic centralized treatment[a]	%	
% tertiary	Percent of tertiary domestic centralized treatment[a]	%	
$N_{rem,PRIMARY}$	Fraction of nitrogen removed from primary domestic centralized treatment (0.1)	No units	1990-2020: IPCC (2019)
$N_{rem,SECONDARY}$	Fraction of nitrogen removed from secondary domestic centralized treatment (0.4)	No units	
$N_{rem,TERTIARY}$	Fraction of nitrogen removed from tertiary domestic centralized treatment (0.9)	No units	
$N_{EFFLUENT,IMP}$	Total nitrogen in effluent discharged to impaired waterbodies	kg N/year	1990-2020: Calculated
$N_{EFFLUENT,NONIMP}$	Total nitrogen in effluent discharged to nonimpaired waterbodies	kg N/year	
EF_{IMP}	Emission factor (discharge to reservoirs/lakes/estuaries) (0.19)	kg N_2O-N/kg N	1990-2020: IPCC (2019)
$EF_{NONIMPr}$	Emissions factor (discharge to other waterbodies) (0.005)	kg N_2O-N/kg N	
$Percent_{IMP}$	Percent of wastewater discharged to impaired waterbodies[a]	%	1990-2010: Set equal to 2010 2010: ERG (2021a)
$Percent_{NONIMP}$	Percent of wastewater discharged to nonimpaired waterbodies[a]	%	

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[11] See emissions from centrally treated aerobic and anaerobic systems for methodological equation calculating $TN_{DOM\_CENTRAL}$.

Variable	Variable Description	Units	Source of Value
			2011: Obtained by linear interpolation 2012: ERG (2021a) 2013-2020: Set equal to 2012

[a] Value for this activity data varies over the Inventory time series.

Industrial Wastewater N_2O Emission Estimates

Nitrous oxide emission estimates from industrial wastewater were added to the inventory for the first time and developed according to the methodology described in the *2019 Refinement*. U.S. industry categories that are likely to produce significant N_2O emissions from wastewater treatment were identified based on whether they generate high volumes of wastewater, whether there is a high nitrogen wastewater load, and whether the wastewater is treated using methods that result in N_2O emissions. The top four industries that meet these criteria and were added to the inventory are meat and poultry processing; petroleum refining; pulp and paper manufacturing; and breweries (ERG 2021a). Wastewater treatment and discharge emissions for these sectors for 2020 are displayed in Table 7-36 below. Table 7-20 contains production data for these industries.

Table 7-36: Total Industrial Wastewater N_2O Emissions by Sector (2020, MMT CO_2 Eq. and Percent)

Industry	N_2O Emissions (MMT CO_2 Eq.)	% of Industrial Wastewater N_2O
Meat & Poultry	0.2	48.1
Petroleum Refineries	0.1	28.4
Pulp & Paper	0.1	22.7
Breweries	+	0.8
Total	**0.5**	**100**

+ Does not exceed 0.5 MMT CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Emissions from Industrial Wastewater Treatment Systems:

More recent research has revealed that emissions from nitrification or nitrification-denitrification processes at wastewater treatment, previously judged to be a minor source, may in fact result in more substantial emissions (IPCC 2019). N_2O is generated as a by-product of nitrification, or as an intermediate product of denitrification. Therefore, N_2O emissions are primarily expected to occur from aerobic treatment systems. To estimate these emissions, the total nitrogen entering aerobic wastewater treatment for each industry must be calculated. Then, the emission factor provided by the *2019 Refinement* is applied to the portion of wastewater that undergoes aerobic treatment.

The total nitrogen that enters each industry's wastewater treatment system is a product of the total amount of industrial product produced, the wastewater generated per unit of product, and the nitrogen expected to be present in each meter cubed of wastewater (IPCC equation 6.13).

Equation 7-45: Total Nitrogen in Industrial Wastewater

$$TN_{INDi} = P_i \times W_i \times TN_i$$

where,

TN_{INDi} = total nitrogen in wastewater for industry *i* for inventory year, kg TN/year
i = industrial sector
P_i = total industrial product for industrial sector *i* for inventory year, t/year

W_i = wastewater generated per unit of production for industrial sector *i* for inventory year, m^3/t product

TNi = total nitrogen in untreated wastewater for industrial sector *i* for inventory year, kg TN/m^3

For the four industries of interest, the total production and the total volume of wastewater generated has already been calculated for CH_4 emissions. For these new N_2O emission estimates, the total nitrogen in the untreated wastewater was determined by multiplying the annual industry production, shown in Table 7-20, by the average wastewater outflow, shown in Table 7-23, and the nitrogen loading in the outflow shown in Table 7-37.

Table 7-37: U.S. Industrial Wastewater Nitrogen Data

Industry	Wastewater Total N (kg N/ m^3)	Source for Total N
Pulp and Paper	0.30[a]	Cabrera (2017)
Meat Processing	0.19	IPCC (2019), Table 6.12
Poultry Processing	0.19	IPCC (2019), Table 6.12
Petroleum Refining	0.051	Kenari et al. (2010)
Breweries – Craft	0.055	IPCC (2019), Table 6.12
Breweries – NonCraft	0.055	IPCC (2019), Table 6.12

[a] Units are kilograms N per air-dried metric ton of production.

Nitrous oxide emissions from industry wastewater treatment are calculated by applying an emission factor to the percent of wastewater (and therefore nitrogen) that undergoes aerobic treatment (IPCC Equation 6.11).

Equation 7-46: N_2O Emissions from Indsutrial Wastewater Treatment Plants

$$N_2O\ Plants_{IND} = \left[\sum_i \left(T_{i,j} \times EF_{i,j} \times TN_{INDi}\right)\right] \times \frac{44}{28}$$

where,

N_2O $Plants_{IND}$ = N_2O emissions from industrial wastewater treatment plants for inventory year, kg N_2O/year

TN_{INDi} = total nitrogen in wastewater from industry *i* for inventory year, kg N/year

$T_{i,j}$ = degree of utilization of treatment/discharge pathway or system *j*, for each industry *i* for inventory year

i = industrial sector

j = each treatment/discharge pathway or system

$EF_{i,j}$ = emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N. 0.015 kg N_2O-N/kg N ERG (2021b)

44/28 = conversion of kg N_2O-N into kg N_2O

For each industry, the degree of utilization (Ti,j)–the percent of wastewater that undergoes each type of treatment–was previously determined for CH_4 emissions and presented in Table 7-22.

Emissions from Industrial Wastewater Treatment Effluent:

Nitrous oxide emissions from industrial wastewater treatment effluent are estimated by multiplying the total nitrogen content of the discharged wastewater effluent by an emission factor associated with the location of the discharge. Where wastewater is discharged to aquatic environments with nutrient-impacted/eutrophic conditions (i.e., water bodies which are rich in nutrients and very productive in terms of aquatic animal and plant life), or environments where carbon accumulates in sediments such as lakes, reservoirs, and estuaries, the additional organic matter in the discharged wastewater is expected to increase emissions.

Equation 7-47: N_2O Emissions from Industrial Wastewater Treatment Effluent

$$N_2O\ Effluent_{IND} = N_{EFFLUENT,IND} \times EF_{EFFLUENT} \times 44/28$$

where,

N_2O $Effluent_{IND}$ = N_2O emissions from industrial wastewater discharge for inventory year (kg N_2O/year)

$N_{EFFLUENT,IND}$ = Total nitrogen in industry wastewater effluent discharged to aquatic environments for inventory year (kg N/year)

$EF_{EFFLUENT}$ = Tier 1 emission factor for wastewater discharged to aquatic environments (0.005 kg N_2O-N/kg N) (IPCC 2019)

44/28 = Conversion of kg N_2O-N into kg N_2O

The total N in treated effluent was determined through use of a nutrient estimation tool developed by EPA's Office of Water (EPA 2019). The Nutrient Tool uses known nutrient discharge data within defined industrial sectors or subsectors, as reported on Discharge Monitoring Reports, to estimate nutrient discharges for facilities within that sector or subsector that do not have reported nutrient discharges but are likely to discharge nutrients. The estimation considers, within each sector or subsector, elements such as the median nutrient concentration and flow, as well as the percent of facilities within the sector or subsector that have reported discharges. Data from 2018 are available for the pulp, paper, and paperboard, meat and poultry processing, and petroleum refining industries. To complete the time series, an industry-specific percent removal of nitrogen was calculated using the total nitrogen in untreated wastewater. See Table 7-38.

Because data for breweries was not available, the removal of nitrogen was assumed to be equivalent to secondary treatment, or 40 percent (IPCC 2019). The Tier 1 emission factor (0.005 kg N_2O/kg N) from IPCC (2019) was used.

Table 7-38: Industrial Wastewater Nitrogen Discharged in 2018 by Sector (kg N)

Industry	N $Effluent_{IND}$ (kg N)	Industry-Specific N Removal Factor
Meat & Poultry	8,773,308	0.082
Petroleum Refineries	1,698,953	0.045
Pulp & Paper	18,809,623	1.08
Breweries	1,069,919	NA

[a] Nitrogen discharged by breweries was estimated as 60 percent of untreated wastewater nitrogen.

Source: ERG (2021a).

Uncertainty

The overall uncertainty associated with both the 2020 CH_4 and N_2O emission estimates from wastewater treatment and discharge was calculated using the *2006 IPCC Guidelines* Approach 2 methodology (IPCC 2006). Uncertainty associated with the parameters used to estimate CH_4 emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, fruits and vegetable processing, ethanol production, petroleum refining, and breweries. Uncertainty associated with the parameters used to estimate N_2O emissions include that of numerous input variables used to model emissions from domestic wastewater and emissions from wastewater from pulp and paper manufacturing, meat and poultry processing, petroleum refining, and breweries. Uncertainty associated with centrally treated constructed wetlands parameters including U.S. population served by constructed wetlands, and emission and conversion factors are from IPCC (2014), whereas uncertainty associated with POTW flow to constructed wetlands and influent BOD and nitrogen concentrations were based on expert judgment (ERG 2021b).

The results of this Approach 2 quantitative uncertainty analysis are summarized in Table 7-39 and Table 7-40. For 2020, methane emissions from wastewater treatment were estimated to be between 11.8 and 22.4 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 35 percent below to 23 percent above the 2020 emissions estimate of 18.3 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 15.3 and 69.3 MMT CO_2 Eq., which indicates a range of approximately 35 percent below to 194 percent above the 2020 emissions estimate of 3.5 MMT CO_2 Eq.

For 1990, methane emissions from wastewater treatment were estimated to be between 14.3 and 26.0 MMT CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 29 percent below to 28 percent above the 1990 emissions estimate of 20.23 MMT CO_2 Eq. Nitrous oxide emissions from wastewater treatment were estimated to be between 11.8 and 50.8 MMT CO_2 Eq., which indicates a range of approximately 29 percent below to 206 percent above the 1990 emissions estimate of 16.6 MMT CO_2 Eq.

Table 7-39: Approach 2 Quantitative Uncertainty Estimates for 2020 Emissions from Wastewater Treatment (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Wastewater Treatment	**CH_4**	**18.3**	**11.8**	**22.4**	**-35%**	**+23%**
Domestic	CH_4	11.8	6.5	14.9	-45%	+26%
Industrial	CH_4	6.4	3.7	10.3	-42%	+60%
Wastewater Treatment	**N_2O**	**23.5**	**15.3**	**69.3**	**-35%**	**+194%**
Domestic	N_2O	23.0	14.4	68.2	-38%	+196%
Industrial	N_2O	0.5	0.5	1.6	-1%	+207%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. *Inventory* QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). This effort included a general or Tier 1 analysis, including the following checks:

- Checked for transcription errors in data input;
- Ensured references were specified for all activity data used in the calculations;
- Checked a sample of each emission calculation used for the source category;
- Checked that parameter and emission units were correctly recorded and that appropriate conversion factors were used;
- Checked for temporal consistency in time series input data for each portion of the source category;
- Confirmed that estimates were calculated and reported for all portions of the source category and for all years;
- Investigated data gaps that affected trends of emission estimates; and
- Compared estimates to previous estimates to identify significant changes.

Calculation-related QC (category-specific, Tier 2) was performed for a portion of the domestic wastewater treatment discharges methodology, which included assessing available activity data to ensure the most complete publicly data set was used and checking historical trends in the data to assist determination of best methodology for filling in the time series for data that are not available annually.

All transcription errors identified were corrected and documented. The QA/QC analysis did not reveal any systemic inaccuracies or incorrect input values.

EPA conducted engagement with stakeholders on development of a U.S.-specific emission factor for nitrous oxide emissions from aerobic wastewater treatment systems. EPA received feedback on study data that reflect U.S. operations and where data collection methods ensure the quality of the emissions data (ERG 2021b).

Recalculations Discussion

Population data were updated to reflect revised U.S. Census Bureau datasets which resulted in changes to 2002 through 2019 values (U.S. Census Bureau 2021). The percent of onsite and collected wastewater were updated to reflect revised American Housing Survey data which resulted in changes to the 2018 and 2019 values (U.S. Census Bureau 2019). These changes affected the timeseries from 2002 through 2019. Protein data were updated to reflect available protein values available for 2014 through 2018 (FAO 2021c). Pulp, paper, and paperboard production data were updated to reflect revised values for 2017 through 2019 (FAO 2021a). Updated red meat production values for 2019, as well as fruits and vegetables processing production values for 2016 through 2019, were updated based on revised data (USDA 2021a; USDA 2021c). Updated ethanol production and petroleum refining production values for 2018 and 2019 were based on revised data (RFA 2021a; RFA 2021b; EIA 2021).

The BOD concentration for wastewater entering constructed wetlands used as tertiary treatment was updated from the secondary treatment standard (30 mg/L) to the median value (9.1 mg/L) provided (EPA 2013). Domestic wastewater treatment and discharge CH_4 emissions decreased an average of 0.3 percent over the time series, with the smallest decrease of 0.04 percent (0 MMT CO_2 Eq.) in 1992 and largest decrease of 3.3 percent (0.1 MMT CO_2 Eq.) in 2019.

EPA revised the domestic wastewater N_2O methodology based on the *2019 Refinement* (IPCC 2019) by updating the factor for non-consumed protein (1.13). EPA also revised the emission factor for centralized aerobic systems which affected 1990 through 2019 (ERG 2021b). All of these changes affected the time series from 1990 through 2019. Domestic wastewater treatment and discharge N_2O emissions decreased an average 11.6 percent over the time series, with the smallest decrease of 10.1 percent (2.6 MMT CO_2 Eq.) in 2018 and largest decrease of 12.4 percent (3.1 MMT CO_2 Eq.) in 2015.

EPA revised the industrial wastewater CH_4 methodology based on the *2019 Refinement* (IPCC 2019): updated emission estimates from discharge of pulp and paper manufacturing wastewater to aquatic environments using a Tier 2 methodology and default emission factor (ERG 2021b). All of these changes affected the time series from 1990 through 2019. Industrial wastewater treatment and discharge CH_4 emissions increased an average of 1.6 percent over the time series, with the smallest increase of 0.9 percent (0.0 MMT CO_2 Eq.) in 2017 and largest increase of 2.6 percent (0.1 MMT CO_2 Eq.) in 1990.

EPA revised the emissions factor for centralized aerobic systems which affected nitrous oxide emissions estimates for 1990 through 2019 (ERG 2021b). Due to the updates to 2018 petroleum refining and pulp, paper, and paperboard manufacturing production data, the total nitrogen entering treatment was updated for 1990 through 2019. All of these changes affected the time series emissions estimates from 1990 through 2019. Industrial wastewater treatment and discharge N_2O emissions decreased an average 5.2 percent over the time series, with the smallest decrease of 5.1 percent (0.02 MMT CO_2 Eq.) in 1995 and largest decrease of 6.0 percent (0.03 MMT CO_2 Eq.) in 2019.

The cumulative effect of these recalculations had a large impact on the overall wastewater treatment emission estimates. Over the time series, the average total emissions decreased by 6 percent from the previous Inventory. The changes ranged from the smallest decrease, 5.1 percent (2.0 MMT CO_2 Eq.), in 1990, to the largest decrease, 7.4 percent (3.3 MMT CO_2 Eq.), in 2019.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three inventory cycles pending time and resource constraints:

- Evaluate a 2020 survey compiling 2018 data on biosolids from the North East Biosolids & Residuals Association (NEBRA). NEBRA expects the final report to be available in September 2021. This report could help refine total sludge data which have been forecasted since 2004.

- Evaluate the use of POTW BOD effluent discharge data from ICIS-NPDES.[12] Currently only half of POTWs report organics as BOD_5 so EPA would need to determine a hierarchy of parameters to appropriately sum all loads. Using these data could potentially improve the current methane emission estimates from domestic discharge.
- Evaluate the use of POTW N effluent discharge data from ICIS-NPDES. Currently only about 80 percent of POTWs report a form of N so EPA would need to determine an appropriate method to scale to the total POTW population. EPA is aware of a method for industrial sources and plans to determine if this method is appropriate for domestic sources.
- Investigate anaerobic sludge digester and biogas data compiled by the Water Environment Federation (WEF) in collaboration with other entities *as a potential source of updated activity data;*
    - *Due to lack of these data, the United States continues to use another method for estimating biogas produced. This method uses the standard 100 gallons/capita/day wastewater generation factor for the United States (Ten-State Standards). However, based on stakeholder input, some regions of the United States use markedly less water due to water conservation efforts so EPA plans to investigate updated sources for this method as well.*
- EPA will continue to look for methods to improve the transparency of the fate of sludge produced in wastewater treatment.

EPA notes the following improvements will continued to be investigated as time and resources allow, but there are no immediate plans to implement until data are available or identified:

- Investigate additional sources for estimating wastewater volume discharged and discharge location for both domestic and industrial sources. For domestic wastewater, the goal would be to provide additional data points along the time series, while the goal for industrial wastewater would be to update the Tier 1 discharge methodology to a Tier 2 methodology.
- Investigate additional sources for domestic wastewater treatment type in place data.
- Review whether sufficient data exist to develop U.S.-specific CH_4 or N_2O emission factors for domestic wastewater treatment systems, including whether emissions should be differentiated for systems that incorporate biological nutrient removal operations; and
- Investigate additional data sources for improving the uncertainty of the estimate of N entering municipal treatment systems.

7.3 Composting (CRF Source Category 5B1)

Composting of organic waste, such as food waste, garden (yard) and park waste, and wastewater treatment sludge and/or biosolids, is common in the United States. Composting reduces the amount of methane-generating waste entering landfills, destroys pathogens in the waste, sequesters carbon, and provides a source of organic matter. Composting can also generate a saleable product and reduce the need for chemical fertilizers when the end product is used as a fertilizer or soil amendment. This source category assumes all composting facilities are commercial, large-scale anaerobic windrow composting facilities with yard trimmings as the main waste stream composted (BioCycle 2017). Facilities using aerobic composting methods (e.g., aerated static piles, in-vessel composting) are operational in the United States, however national estimates of the material processed by these facilities are not readily available and therefore not included.

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[12] ICIS-NPDES refers to EPA's Integrated Compliance Information System – National Pollutant Discharge Elimination System.

Composting naturally converts a large fraction of the degradable organic carbon in the waste material into carbon dioxide (CO_2) through aerobic processes without anthropogenic influence. With anthropogenic influences (e.g., at commercial or large on-site composting operations), anaerobic conditions can be created in sections of the compost pile when there is excessive moisture or inadequate aeration (or mixing) of the compost pile, resulting in the formation of methane (CH_4). Methane in aerobic sections of a windrow pile are generally oxidized by microorganisms, which convert the CH_4 to CO_2 emissions. Even though CO_2 emissions are generated, they are not included in net greenhouse gas emissions for composting. Consistent with the *2006 IPCC Guidelines*, net CO_2 flux from carbon stock changes in waste material are estimated and reported under the LULUCF sector. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few percent of the initial C content in the material (IPCC 2006). Depending on how well the compost pile is managed, nitrous oxide (N_2O) emissions can also be produced. The formation of N_2O depends on the initial nitrogen content of the material and is mostly due to nitrogen oxide (NO_x) denitrification during the thermophilic and secondary mesophilic stages of composting (Cornell 2007). Emissions vary and range from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (IPCC 2006). Animal manures are typically expected to generate more N_2O than, for example, yard waste, however data are limited.

From 1990 to 2020, the amount of waste composted in the United States (see Table 7-42) increased from 3,810 kt to 22,774 kt. There was some fluctuation in the amount of waste composted between 2006 to 2009 where a peak of 20,063 kt composted was observed in 2008, which decreased to 18,838 kt composted the following year, presumably driven by the economic crisis of 2009 (data not shown). Since 2009, the amount of waste composted has gradually increased, and when comparing 2010 to 2020, a 24 percent increase in waste composted is observed. Emissions of CH_4 and N_2O from composting from 2010 to 2020 have increased by the same percentage.

In 2020, CH_4 emissions from composting (see Table 7-40 and Table 7-41) were 2.3 MMT CO_2 Eq. (91 kt), and N_2O emissions from composting were 2.0 MMT CO_2 Eq. (7 kt), representing consistent emissions trends when compared to 2019. The wastes composted primarily include yard trimmings (grass, leaves, and tree and brush trimmings) and food scraps from the residential and commercial sectors (such as grocery stores; restaurants; and school, business, and factory cafeterias). The composted waste quantities reported here do not include small-scale backyard composting and agricultural composting mainly due to lack of consistent and comprehensive national data. Additionally, it is assumed that backyard composting tends to be a more naturally managed process with less chance of generating anaerobic conditions and CH_4 and N_2O emissions. Agricultural composting is accounted for in Volume 4, Chapter 5 (Cropland) of this Inventory, as most agricultural composting operations are assumed to then land-apply the resultant compost to soils.

The growth in composting since the 1990s and specifically over the past decade is attributable to the following factors: (1) the enactment of legislation by state and local governments that discouraged the disposal of yard trimmings and food waste in landfills, (2) yard trimming collection and yard trimming drop off sites provided by local solid waste management districts/divisions, (3) an increased awareness of the environmental benefits of composting, and (4) loans or grant programs to establish or expand composting infrastructure.

Most bans or diversion laws on the disposal of yard trimmings were initiated in the early 1990s by state or local governments (U.S. Composting Council 2010). California, for example, enacted a waste diversion law for organics including yard trimmings and food scraps in 1999 (AB939) that required jurisdictions to divert 50 percent of the waste stream by 2000, or be subjected to fines. Currently, 22 states representing about 44 percent of the nation's population have enacted such legislation (NERC 2020). There are many more initiatives at the metro and municipal level across the United States. Roughly 4,713 composting facilities exist in the United States with most (57.2 percent) composting yard trimmings only (BioCycle 2017).

In the last decade, bans and diversions for food waste have also become more common. As of April 2019, six states (California, Connecticut, New York, Massachusetts, Rhode Island, Vermont) and seven municipalities (Austin, TX; Boulder, CO; Hennepin County, MN; Metro, OR; New York City, NY; San Francisco, CA; Seattle, WA) had implemented organic waste bans or mandatory recycling laws to help reduce organic waste entering landfills, with most having taken effect after 2013 (Harvard Law School and CET 2019). In most cases, organic waste reduction in landfills is accomplished by following recycling guidelines, donating excess waste for human consumption, or by sending waste to organics processing facilities (Harvard Law School and CET 2019). An example of an organic waste ban as implemented by California is the California Mandatory Recycling Law (AB1826), which requires companies to comply with organic waste recycling procedures if they produce a certain amount of organic waste and took effect on January 1, 2015 (Harvard Law School and CET 2019). In 2017, *BioCycle* released a report in which 27 of 43 states that responded to their organics recycling survey noted that food waste (collected residential, commercial, institutional, and industrial food waste) was recycled via anaerobic digestion and/or composting. These 27 states reported an estimated total of 1.8 million tons of food waste diverted from landfills in 2016 (BioCycle 2018b). There are a growing number of initiatives to encourage households and businesses to compost or beneficially reuse food waste.

Table 7-40: CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq.)

Activity	1990		2005		2016	2017	2018	2019	2020
CH_4	0.4		1.9		2.3	2.5	2.3	2.3	2.3
N_2O	0.3		1.7		2.0	2.2	2.0	2.0	2.0
Total	**0.7**		**3.5**		**4.3**	**4.6**	**4.3**	**4.3**	**4.3**

Note: Totals may not sum due to independent rounding.

Table 7-41: CH_4 and N_2O Emissions from Composting (kt)

Activity	1990		2005		2016	2017	2018	2019	2020
CH_4	15		75		91	98	90	91	91
N_2O	1		6		7	7	7	7	7

Methodology

Methane and N_2O emissions from composting depend on factors such as the type of waste composted, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the composting process.

The emissions shown in Table 7-40 and Table 7-41 were estimated using the IPCC default (Tier 1) methodology (IPCC 2006), which is the product of an emission factor and the mass of organic waste composted (note: no CH_4 recovery is expected to occur at composting operations in the emission estimates presented):

Equation 7-48: Greenhouse Gas Emission Calculation for Composting

$$E_i = M \times EF_i$$

where,

E_i = CH_4 or N_2O emissions from composting, kt CH_4 or N_2O
M = mass of organic waste composted in kt
EF_i = emission factor for composting, 4 t CH_4/kt of waste treated (wet basis) and 0.3 t N_2O/kt of waste treated (wet basis) (IPCC 2006)
i = designates either CH_4 or N_2O

Per IPCC Tier 1 methodology defaults, the emission factors for CH_4 and N_2O assume a moisture content of 60 percent in the wet waste (IPCC 2006). While the moisture content of composting feedstock can vary significantly by type, composting as a process ideally proceeds between 40 to 65 percent moisture (University of Maine 2016; Cornell 1996).

Estimates of the quantity of waste composted (M, wet weight as generated) are presented in Table 7-42 for select years. Estimates of the quantity composted for 1990, 2005, and 2014 to 2015 were taken from EPA's *Advancing Sustainable Materials Management: Facts and Figures* 2015 (EPA 2018); the estimates of the quantities composted for 2016 to 2018 were taken from EPA's *Advancing Sustainable Materials Management: 2018 Tables and Figures* (EPA 2020); the estimate of the quantity composted for 2019 and 2020 were extrapolated using the 2018 quantity composted and a ratio of the U.S. population growth between 2018 to 2019, and 2019 to 2020, respectively (U.S.

Census Bureau 2021). New to this inventory are estimates of waste composted by commercial facilities in Puerto Rico provided by EPA Region 2 (Kijanka 2020). Only limited information across the time series was provided. This inventory includes waste composted for 2017, 2018, and/or 2019 from three facilities in Puerto Rico, ranging from 1,200 tons to a high of 15,021 tons. The average waste composted for these years was used as the annual amount composted for the respective facility for years the facility was operational, but for which annual waste composted data are lacking. Additional efforts are being made to fill these historical data gaps.

Table 7-42: U.S. Waste Composted (kt)

Activity	1990		2005		2016	2017	2018	2019	2020
Waste Composted	3,810		18,655		22,795	24,501	22,594	22,709	22,774

Uncertainty

The major uncertainty drivers are the assumption that all composting emissions come from commercial windrow facilities and the use of default emission factors (IPCC 2006) which are tied to a homogenous mixture of waste processed across the country (largely yard trimmings). Data presented by BioCycle (BioCycle 2017) confirm most composting operations use the windrow method and yard trimmings are the largest share of material composted across the country, but there are other composting methods used and waste characteristics will vary at a facility level. The material composted is estimated using a mass balance flows model with end results presented in the EPA Sustainable Materials Management Reports. No primary data on actual annual quantities of material composted are collected by the Inventory compilation team or the EPA Sustainable Materials Management Report compilation team, thus, the activity data used to generate greenhouse gas emissions are also a source of uncertainty. Additionally, there are composting operations in Puerto Rico and U.S. territories that are not explicitly included in the national quantity of material composted as reported in the EPA Sustainable Materials Management Reports because the methodological scope does not include Puerto Rico and U.S. territories. EPA took steps to include emissions from Puerto Rico and U.S. Territories beginning in the 1990 to 2020 inventory and will continue to seek out additional data in future Inventories.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±58 percent for the Approach 1 methodology. A ±30 percent uncertainty factor is applied to the annual amount of material composted (i.e., the activity data) and a ±50 percent uncertainty factor is applied to both the CH_4 and N_2O emission factors. These uncertainty factors were developed using expert judgment. Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±58 percent.

Emissions from composting in 2020 were estimated to range between 1.8 and 6.8 MMT CO_2 Eq., which indicates a range of 58 percent below to 58 percent above the 2020 emission estimate of each gas (see Table 7-43).

Table 7-43: Approach 1 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Composting (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Composting	CH_4	2.3	0.9	3.6	-58%	+58%
	N_2O	2.0	0.8	3.2	-58%	+58%
	Total	**4.3**	**1.8**	**6.8**	**-58%**	**+58%**

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

The U.S. population estimate for 2019 was revised with current U.S. Census Bureau Data from Table 1. *Annual Estimates of the Resident Population for the United States, Regions, States, the District of Columbia, and Puerto Rico: April 1, 2010 to July 1, 2019; April 1, 2020; and July 1, 2020 (U.S. Census Bureau, 2021)*. Because the 2019 composting estimates are extrapolated based on population growth, this recalculation also resulted in a minor increase in the quantity of material composted. The quantity of material composted in 2019 (extrapolated based on population growth) increased by 6 kt from the previous Inventory report. In addition to this recalculation, the amount of waste composted in PR is added onto the 2019 recalculated value, resulting in 22,709 kt of waste composted in 2019, a 0.09% increase from 22,687 kt in the previous Inventory report.

Efforts have been made to improve the completeness of the composting Inventory by incorporating composted waste from U.S. Territories. In 2016, EPA conducted a desk-based investigation into industrial/commercial composting facilities in the U.S. Territories and identified facilities in Puerto Rico. Historical data is generally lacking for identified facilities in Puerto Rico and service disruptions have occurred in previous years due to weather-related damage. Quantities of material composted at two facilities between 2017 to 2019 and for one facility in 2019 have been obtained and incorporated into the current 1990 to 2020 Inventory. These three facilities began operating in 1998, 2007, and 2012, respectively. The average of waste composted for these years was used as a general estimate of waste composted for each year these facilities have been operational in the time series. Incorporating material composted from these three facilities resulted in a minimal, if any, increase of less than 0.5 percent in total material composted and emissions across the time series. Additional efforts are being made to collect historical and current (i.e., 2020) estimates of the quantity of waste composted by these three facilities. This data may be incorporated into future Inventories as a methodological improvement.

Planned Improvements

EPA completed a literature search on emission factors and composting systems and management techniques that were documented in a draft technical memorandum. The purpose of this literature review was to compile all published emission factors specific to various composting systems and composted materials in the United States to determine whether the emission factors used in the current methodology can be revised or expanded to account for geographical differences and/or differences in composting systems used. For example, outdoor composting processes in arid regions typically require the addition of moisture compared to similar composting processes in wetter climates. In general, there is a lack of facility-specific data on the management techniques and sum of material composted to enable the incorporate of different emission factors. EPA will continue to seek out more detailed data on composting facilities to enable this improvement in the future.

Relatedly, EPA has received comments during previous Inventory cycles recommending that calculations for the composting sector be based on waste subcategories (i.e., leaves, grass and garden debris, food waste) and category-specific moisture contents. At this time, EPA is not aware of any available datasets which would enable estimations to be performed at this level of granularity. EPA will continue to search for data which could lead to the development of subcategory-specific composting emission factors to be used in future Inventory cycles.

EPA will also continue to seek out activity data including processing capacity and years of operation for commercial composting facilities in U.S. Territories such as Guam for inclusion in a future national Inventory.

7.4 Anaerobic Digestion at Biogas Facilities (CRF Source Category 5B2)

Anaerobic digestion is a series of biological processes in the absence of oxygen in which microorganisms break down organic matter, producing biogas and soil amendments. The biogas primarily consists of CH_4, biogenic CO_2, and trace amounts of other gases such as N_2O (IPCC 2006) and is often combusted to produce heat and power, or further processed into renewable natural gas or for use as a transportation fuel. Digester gas contains approximately 65 percent CH_4 (a normal range is 55 percent to 65 percent) and approximately 35 percent CO_2 (WEF 2012; EPA 1993). Methane emissions may result from a fraction of the biogas that is lost during the process due to leakages and other unexpected events (0 to 10 percent of the amount of CH_4 generated, IPCC 2006), collected biogas that is not completely combusted, and entrained gas bubbles and residual gas potential in the digested sludge. Carbon dioxide emissions are biogenic in origin and should be reported as an informational item in the Energy Sector (IPCC 2006). Volume 5 Chapter 4 of the *2006 IPCC Guidelines* notes that at biogas plants where unintentional CH_4 emissions are flared, CH_4 emissions are likely to be close to zero.

Anaerobic digesters differ based on the operating temperature, feedstock type and moisture content, and mode of operation. The operating temperature dictates the microbial communities that live in the digester. Mesophilic microbes are present at temperatures ranging from 85 to 100 degrees Fahrenheit while thermophilic microbes thrive at temperatures ranging from 122 to 140 degrees Fahrenheit (WEF 2012). Digesters may process one or more types of feedstock, including food waste; municipal wastewater solids; livestock manure; industrial wastewater and residuals; fats, oils, and grease; and other types of organic waste streams. Co-digestion (multiple feedstocks) is employed to increase methane production in cases where an organic matter type does not break down easily. In co-digestion, various organic wastes are decomposed in a singular anaerobic digester by using a combination of manure and food waste from restaurants or food processing industry, or a combination of manure and waste from energy crops or crop residues (EPA 2016). The moisture content of the feedstock (wet or dry) impacts the amount of biogas generation. Wet anaerobic digesters process feedstock with a solids content less than 15 percent while dry anaerobic digesters process feedstock with a solids content greater than 15 percent (EPA 2020). Digesters may also operate in batch or continuous mode, which affects the feedstock loading and removal. Batch anaerobic digesters are manually loaded with feedstock all at once and then manually emptied while continuous anaerobic digesters are continuously loaded and emptied with feedstock (EPA 2020).

The three main categories of anaerobic digestion facilities included in national greenhouse gas inventories include the following:

- Anaerobic digestion at biogas facilities, or stand-alone digesters, typically manage food waste from different sources, including food and beverage processing industries. Some stand-alone digesters also co-digest other organics such as yard waste.
- On-farm digesters that manage organic matter and reduce odor generated by farm animals or crops. On-farm digesters are found mainly at dairy, swine, and poultry farms where there is the highest potential for methane production to energy conversion. On-farm digesters may also accept food waste as feedstock for co-digestion.
- Digesters at water resource recovery facilities (WRRF) produce biogas through the treatment and reduction of wastewater solids. Some WRRF facilities may also accept and co-digest food waste.

This section focuses on stand-alone anaerobic digestion at biogas facilities. Emissions from on-farm digesters are included Chapter 5 (Agriculture) and AD facilities at WRRFs are included in Section 7.2 (Wastewater Treatment).

From 1990 to 2020, the estimated amount of waste managed by stand-alone digesters in the United States increased from approximately 786 kt to 8,263 kt, an increase of 951 percent. As described in the Uncertainty section, no data sources present the annual amount of waste managed by these facilities prior to 2015 when the EPA began a comprehensive data collection survey. Thus, the emission estimates in the early part of the time series are general estimates, extrapolated from data collected later in the time series (i.e., 2015 and later). The steady increase in the amount of waste processed over the time series is likely driven by increasing interest in using waste as a renewable energy source and other organics diversion goals.

In 2020, emissions from stand-alone anaerobic digestion at biogas facilities were approximately 0.2 MMT CO_2 Eq. (6 kt) (see Table 7-44 and Table 7-45).

Table 7-44: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (MMT CO_2 Eq.) from 1990-2020

Activity	1990		2005		2016	2017	2018	2019	2020
CH_4 Generation	+		0.05		0.2	0.2	0.2	0.2	0.2
CH_4 Recovered	(+)		(+)		(+)	(+)	(+)	(+)	(+)
CH_4 Emissions	**+**		**+**		**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+ Does not exceed 0.05 MMT.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table 7-45: CH_4 Emissions from Anaerobic Digestion at Biogas Facilities (kt) from 1990-2020

Activity	1990		2005		2016	2017	2018	2019	2020
CH_4 Generation	1		2		7	7	7	7	7
CH_4 Recovered	(+)		(+)		(0.7)	(+)	(0.5)	(0.5)	(0.5)
CH_4 Emissions	**1**		**2**		**7**	**6**	**6**	**6**	**6**

+ Does not exceed 0.5 kt.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Methodology

Methane emissions from anaerobic digestion depend on factors such as the type of waste managed, the amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content (e.g., wet and fluid versus dry and crumbly), and aeration during the digestion process.

The emissions presented in Table 7-44 were estimated using the IPCC default (Tier 1) methodology (Volume 5, Chapter 4, IPCC 2006) given in Equation 7-49 below, which is the product of an emission factor and the mass of organic waste processed. Only CH_4 emissions are estimated because N_2O emissions are considered negligible (IPCC 2006). Some Tier 2 data are available (annual quantity of waste digested) for the later portion of the time series (2015 and later).

Equation 7-49: Methane Emissions Calculation for Anaerobic Digestion

$$CH_4\ Emissions = \sum_i (M_i \times EF_i) \times 10^{-3} - R$$

where,

CH_4 Emissions = total CH_4 emissions in inventory year, Gg CH_4
M_i = mass of organic waste treated by biological treatment type *i*, Gg, see Table 7-46
EF = emission factor for treatment *i*, g CH_4/kg waste treated, 0.8 Mg/Gg CH_4
i = anaerobic digestion
R = total amount of CH_4 recovered in inventory year, Gg CH_4

Equation 7-50: Recovered Methane Estimation for Anaerobic Digestion

$$R = Biogas \times 0.0283 \times \frac{minutes}{year} \times Biogas\ CH_4\ Density \times C_{CH4} \times \frac{1}{10^9} \times (1 - DE)$$

where,

Biogas = the annual amount of biogas produced, standard cubic feet per minute (scfm)

0.0283	=	conversion factor cubic meter/cubic feet
525,600	=	minutes per year
662	=	CH_4 density in biogas (EPA 1993), g CH_4/m^3 CH_4
65%	=	C_{CH4}, concentration of CH_4 in the biogas (WEF 2012; EPA 1993)
1/10^9	=	conversion factor, grams to kt
0.99	=	destruction efficiency for combustion unit

Per IPCC Tier 1 methodology defaults, the emission factor for CH_4 assumes a moisture content of 60 percent in the wet waste (IPCC 2006). Both liquid and solid wastes are processed by stand-alone digesters and the moisture content entering a digester may be higher. One emission factor recommended by the *2006 IPCC Guidelines* (0.8 Mg/Gg CH_4) is applied for the entire time series (IPCC 2006 Volume 5, Chapter 4, Table 4.1).

The annual quantity of waste digested is sourced from recent EPA surveys of anaerobic digestion facilities (EPA 2018, 2019, and 2021). The EPA was granted the authority to survey anaerobic digestion facilities that process food waste annually through an Information Collection Request (ICR No. 2533.01). The scope includes stand-alone and co-digestion facilities (on-farm and water resource recovery facilities [WRRF]). Three reports with survey results have been published to date:

- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2015: Survey Results* (EPA 2018)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in 2016: Survey Results* (EPA 2019)
- *Anaerobic Digestion Facilities Processing Food Waste in the United States in (2017 & 2018): Survey Results* (EPA 2021)

These reports present aggregated survey data including the annual quantity of waste processed by digester type (i.e., stand-alone, on-farm, and WRRF); waste types accepted; biogas generation and end use; and more. The aggregated data presented in the EPA reports are underestimates of the actual amount of processed waste and biogas produced because (1) surveys rarely achieve a 100 percent response rate and facilities in each survey year did not respond to the survey; (2) EPA focused this survey on facilities that process food waste, and there may be additional operational digesters that are not located on farms or at wastewater treatment plants; and (3) EPA has done due diligence to identify all stand-alone digesters that process food waste but may not have identified all facilities across the United States and its territories. The amount of waste digested as reported in the survey reports were assumed to be in wet weight; the majority of stand-alone digesters were found to be wet and mesophilic (EPA 2019).

The annual quantity of waste digested for 1990 to 2014 (only 1990 and 2005 are shown in Table 7-46) was estimated by multiplying the count of estimated operating facilities (as presented in Table 7-47) by the weighted average of waste digested in 2015 and 2016 collected through EPA's survey data (EPA 2018; EPA 2019). Masked survey responses of food and non-food waste processed were shared with the Inventory team by the EPA team leading the EPA AD Data Collection Surveys. This provided an accurate count of the number of facilities that provided annual quantities of digested waste, which matters for the weighted average. The weighted average applied to the current inventory is calculated as follows for 1990 to 2014:

Equation 7-51: Weighted Average of Waste Processed

$$Weighted\ Average\ Waste\ Processed = \frac{(W_{2016} \times Fac_{2016} + W_{2015} \times Fac_{2015})}{(Fac_{2016} + Fac_{2015})}$$

where,

W = total waste processed in the respective survey year, food and non-food waste (short tons).

Fac = the number of facilities that reported an amount of waste processed in the respective survey year. Note the number of facilities that provided an annual quantity of waste processed data was internally shared and differs from the total number of facilities that responded to the EPA surveys as presented in EPA (2018, 2019).

Estimates of the quantity of waste digested (M, wet weight as generated) are presented in Table 7-46 for select years and the number of facilities that reported annual quantities of waste digested to the EPA survey were 45 and 44 in 2015 and 2016, respectively (using masked facility data provided by the EPA AD survey data collection team).

Estimates of the quantity of waste digested for 1990 to 2014 are calculated by multiplying the weighted average of waste digested from 2015 and 2016 survey data (216,494 short tons) by the count of operating facilities in each year. This calculation assumes that each facility operates continuously from the first year of operation for the remainder of the time series. Additional efforts will be made to quantify the number of operating facilities and estimates of the total waste digested by year for future Inventories as described in the Planned Improvements section. Estimates of the quantity digested for 2015 and 2016 were taken from EPA's AD survey data (EPA 2018; EPA 2019, respectively). The estimate of waste digested for 2019 and 2020 were extrapolated using the average of the waste digested from the 2017 and 2018 survey data (EPA 2021) as a proxy. Data for these years will be updated as future EPA survey reports are published.

Table 7-46: U.S. Waste Digested (kt) from 1990-2020

Activity	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Waste Digested[a]	786	2,357	9,305	8,206	8,320	8,263	8,263

[a] The amount of waste digested primarily consists of food waste. The amount processed for all years is likely an underestimate because the estimates were developed from survey data provided by operating facilities for 2015 to 2018 (EPA 2018; EPA 2019; EPA 2021). Facilities that did not respond to the EPA surveys are not included and all years except 2015 to 2018 are estimated using assumptions regarding the number of operating facilities and the weighted average of waste digested. Additionally, the liquid portion of the waste digested in 2015 and 2016 are not included due to limited information on the specific waste types to perform the unit conversion to kt. EPA converted liquid waste to tons for 2018 and 2019 using a conversion factor of 3.8 pounds per gallon (EPA 2021). The weighted average of waste digested in 2015 and 2016 (as reported in EPA 2018 and 2019) is used as the average for 1990 to 2014, and the average waste digested as reported in EPA (2021) is used as a proxy for years 2019 to 2020.

The estimated count of operating facilities is calculated by summing the count of digesters that began operating by year over the time series. The year a digester began operating is sourced from EPA (2021). This assumes all facilities are in operation from their first year of operation throughout the remainder of the time series, including facilities prior to 1990. This is likely an overestimate of facilities operating per year but does not necessarily translate to an overestimate in the amount of waste processed because a weighted average of waste processed for the surveyed facilities is applied to these years. The number of facilities in 1990 to 2014 are directly used in calculating the emissions, while the directly reported annual amount of waste processed from the survey data are used for 2015 to 2020.

Table 7-47: Estimated Number of Stand-Alone AD Facilities Operating[a] from 1990-2020

Year	1990	2005	2016	2017	2018	2019	2020
Estimated Count of Operational Facilities	4	12	62	68	68	68	68

[a] The count of operational facilities was visually estimated from Figure 5 in EPA (2021), which presents the count of the first year of digester operation. The number of operational facilities by year is assumed to be the cumulative total from the prior year. This method assumes all facilities are operating from 1990, or their first year of operation, to 2020. The number of facilities operating between 2015 to 2018 are equal to the number of facilities surveyed by EPA (EPA 2018, 2019, and 2021). The number of facilities operating in 2019 and 2020 are assumed to be the same as the last survey report data year, i.e., 2018 as reported in EPA (2021). These assumptions are further discussed in the Methodology and Time-Series Consistency section.

Activity data for the amount of biogas recovered (R in the emission calculation equation) is limited across the time series. Currently, there are only four data points (2015, 2016, 2017, and 2018) represented for the entire sector, as reported in the EPA AD Data Collection Survey reports (EPA 2018, 2019, and 2021). The total quantity of collected biogas from the survey respondents is reported in standard cubic feet per minute (scfm) as shown in Table 7-48**.** Volume 5 Chapter 4 of the 2006 IPCC Guidelines notes that only emissions from flaring can be reported under the waste sector. The top three known uses of the biogas generated by stand-alone digesters are combined heat and power (CHP), the production of electricity that is sold to the grid, and using the biogas to fuel boilers and furnaces to heat the digestor and other facility spaces (EPA 2018; EPA 2019). Thus, no biogas is assumed to be flared.

Table 7-48: Estimated Biogas Produced and Methane Recovered from Anaerobic Digestion at Biogas Facilities Operating from 1990-2020[a]

Activity	1990		2005		2016	2017	2018	2019	2020
Total Biogas Produced (scfm)[b]	767		2,301		10,498	6,402	7,282	6,842	6,842
R, recovered CH_4 from biogas (kt)[c]	(0.05)		(0.14)		(0.67)	(0.41)	(0.47)	(0.49)	(0.49)

[a] Total biogas produced in standard cubic feet per minute (scfm) was reported in aggregate in the EPA survey data (EPA 2018, 2019, 2021) for 2015 to 2018. The quantities presented in this table are likely underestimates because not all operational facilities provided a survey response to the EPA AD Data Collection Surveys.

[b] Data for all years in the time series except for 2015 and 2016 are extrapolated using the average of the total biogas collected between 2015 to 2018, divided by the average number of survey responses to generate a weighted average estimate of biogas collected per facility, which is then multiplied by the total facility count (as shown in Table 7-47).

[c] The quantity of CH_4 recovered from the biogas produced is estimated for all years except 2015 to 2018, which are taken from EPA (2018), EPA (2019), and EPA (2021).

Note: Parentheses indicate negative values.

Uncertainty

The methodology applied for the 1990 to 2014 emissions estimates should be considered a starting point to build on in future years if additional historical data become available. Four years of facility-provided data are available (2015 to 2018) while the rest of the time series is estimated based on an assumption of facility counts and the 2015 and 2016 weighted average annual waste digested as calculated from survey data. The major limitations, and uncertainty drivers in the emissions estimates, are related to the uncertainty in assumptions to ensure completeness across the time series and the limitations in the EPA AD survey data, as described below:

1. The EPA AD survey (EPA 2018; EPA 2019; EPA 2021) did not receive a 100 percent response rate, meaning that the survey data represent a portion, albeit the majority, of stand-alone digesters, annual waste processed, and biogas recovered. The methodology applied here did not attempt to estimate waste digested by facilities that did not respond to the survey, which likely underestimates the quantity of waste digested and CH_4 emissions.
2. The EPA AD survey data (EPA 2018; EPA 2019) present both food and non-food waste digested. The non-food waste was reported as liquid (gallons) and solid (tons). The quantity of liquid waste managed is not included in the estimated quantity of annual waste digested for 2015 and 2016, which is used as a proxy for 1990 to 2014 because data on the waste types are not available to convert the quantity from gallons to tons. This slightly underestimates the quantity of waste digested and CH_4 emissions. EPA (2021) did convert the liquid waste managed to tons for 2017 and 2018 using a general conversion factor.
3. The assumption required to estimate the activity data for 1990 to 2014 may overestimate the number of facilities in operation because it assumes that each facility operates from its start year for the entire time series (i.e. facility closures are not taken into account). This introduces a large amount of uncertainty in the estimates compared to years where there is directly reported survey data. It is unclear whether this under- or over-estimates the quantity of waste digested and CH_4 emissions.

The estimated uncertainty from the *2006 IPCC Guidelines* is ±54 percent for the Approach 1 methodology.

Emissions from anaerobic digestion at biogas facilities in 2020 were estimated to be between 0.1 and 0.2 MMT CO_2 Eq., which indicates a range of 54 percent below to 54 percent above the 2020 emission estimate of CH_4 (see Table 7-49). A ±20 percent uncertainty factor is applied to the annual amount of material digested (i.e., the activity data), which was developed with expert judgment. A ±50 percent default uncertainty factor is applied to the CH_4

emission factor (IPCC 2006). Using the IPCC's error propagation equation (Equation 3.1 in IPCC 2006 Volume 1, Chapter 3), the combined uncertainty percentage is ±54 percent.

Table 7-49: Approach 1 Quantitative Uncertainty Estimates for Emissions from Anaerobic Digestion (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Anaerobic Digestion at Biogas Facilities	CH_4	0.2	0.1	0.2	-54%	+54%

QA/QC and Verification

General QA/QC procedures were applied to data gathering and input, documentation, and calculations consistent with the *U.S. Inventory QA/QC Plan*, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). No errors were found for the current Inventory.

Recalculations Discussion

EPA incorporated the EPA (2021) AD Data Collection Survey Data for 2017 and 2018 into the current (1990 to 2020) Inventory. Recalculations were made to the number of operating facilities compared to the 1990 to 2019 Inventory for the following years: 1992, 1999, 2001, 2004, 2006, 2008, and 2010 to 2014. The number of operational facilities was sourced from EPA (2019) in the 1990 to 2019 Inventory, and facilities counts for the aforementioned years changed slightly (plus or minus one facility) in EPA (2021). Due to how the emissions are estimated for 1990 to 2014, a change in the number of facilities in any of these years will impact the facility count for all subsequent years in addition to the estimated annual quantities of waste digested and net CH_4 emissions. The recalculations resulted in changes in net CH_4 emissions of less than 0.5 kt each year.

Recalculations were also made to the 2017 to 2019 emissions estimates with the inclusion of the EPA (2021) survey data for 2017 and 2018. The estimated quantity of waste digested decreased by 1,428 kt, 1,314 kt, and 1,371 kt in 2017, 2018, and 2019, respectively. The decrease in annual waste digested resulted in a decrease in net CH_4 emissions by approximately 0.9 kt each year from 2017 to 2019.

Planned Improvements

EPA will continue to incorporate survey data from future EPA AD Data Collection Surveys when the survey data are published. These revisions will change the estimated emissions for later years in the time series (e.g., 2019, 2020).

EPA will also re-assess how best to estimate annual waste processed using proxy data for years between the EPA AD Data Collection Survey reports as needed (e.g., for 2019, 2020). The methodology described here assumes the same average amount of waste is processed each year for 2019 and 2020.

EPA will conduct additional desk-based research to improve the estimated number of operational facilities by year prior to 2015 and how best to estimate the quantity of waste processed per year by these facilities with the goal of better estimating the annual quantity of waste digested between 1990 to 2014. Available data will also be compiled for facilities that did not directly respond to the EPA AD Data Collection surveys for completeness.

EPA will investigate the amount of recovered biogas for years prior to 2015 (i.e., the years prior to the EPA AD Data Collection Surveys). Currently, partial data of recovered biogas are available between 2015 to 2018 from the EPA AD Data Collection Surveys. The primary purpose of this improvement will be to understand whether the range of recovered biogas from the survey data are reflective of earlier years in the time series.

The uncertainty assessment will be further reviewed to confirm the appropriateness of the uncertainty factor(s) to be applied.

7.5 Waste Incineration (CRF Source Category 5C1)

As stated earlier in this chapter, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emissions from the incineration of waste are accounted for in the Energy sector rather than in the Waste sector because almost all incineration of municipal solid waste (MSW) in the United States occurs at waste-to-energy facilities where useful energy is recovered. Similarly, the Energy sector also includes an estimate of emissions from burning waste tires and hazardous industrial waste, because virtually all of the combustion occurs in industrial and utility boilers that recover energy. The incineration of waste in the United States in 2020 resulted in 13.5 MMT CO_2 Eq. of emissions. For more details on emissions from the incineration of waste, see Section 3.3 of the Energy chapter.

Additional sources of emissions from waste incineration include non-hazardous industrial waste incineration and medical waste incineration. As described in Annex 5 of this report, data are not readily available for these sources and emission estimates are not provided.

An analysis of the likely level of medical waste incineration emissions was conducted based on a 2009 study of hospital/ medical/ infectious waste incinerator (HMIWI) facilities in the United States (RTI 2009). Based on that study's information of waste throughput and an analysis of the fossil-based composition of the waste, it was determined that annual greenhouse gas emissions for medical waste incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC. More information on this analysis is provided in Annex 5.

Furthermore, an analysis was conducted on the likely level of sewage sludge incineration emissions based on the total amount of sewage sludge generated and assumed percent incineration. Based on assumed amount of sludge incinerated and non-CO_2 factors for solid biomass it was determined that annual greenhouse gas emissions for sewage sludge incineration would be below 500 kt CO_2 Eq. per year and considered insignificant for the purposes of Inventory reporting under the UNFCCC.

7.6 Waste Sources of Precursor Greenhouse Gases

In addition to the main greenhouse gases addressed above, waste generating and handling processes are also sources of precursors to greenhouse gases. The reporting requirements of the UNFCCC[13] request that information be provided on precursor emissions, which include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide (SO_2). These gases are not direct greenhouse gases, but can indirectly impact Earth's radiative balance by altering the concentrations of other greenhouse gases (e.g., tropospheric ozone) and atmosphere aerosol (e.g., particulate sulfate). Total emissions of NO_x, CO, NMVOCs, and SO_2 from waste sources for the years 1990 through 2020 are provided in Table 7-50.

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[13] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

Table 7-50: Emissions of NO_x, CO, NMVOC, and SO_2 from Waste (kt)

Gas/Source	1990	2005	2016	2017	2018	2019	2020
NO_x	**+**	**2**	**1**	**1**	**1**	**1**	**1**
Landfills	+	2	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0
CO	**1**	**7**	**6**	**5**	**5**	**5**	**5**
Landfills	1	6	6	5	5	5	5
Wastewater Treatment	+	+	+	+	+	+	+
Miscellaneous[a]	+	0	0	0	0	0	0
NMVOCs	**673**	**114**	**57**	**52**	**52**	**52**	**52**
Wastewater Treatment	57	49	25	22	22	22	22
Miscellaneous[a]	557	43	22	20	20	20	20
Landfills	58	22	11	10	10	10	10
SO_2	**+**	**1**	**1**	**1**	**1**	**1**	**1**
Landfills	+	1	1	1	1	1	1
Wastewater Treatment	+	0	0	0	0	0	0
Miscellaneous[a]	+	0	0	0	0	0	0

+ Does not exceed 0.5 kt.

[a] Miscellaneous includes TSDFs (Treatment, Storage, and Disposal Facilities under the Resource Conservation and Recovery Act [42 U.S.C. § 6924, SWDA § 3004]) and other waste categories.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Emission estimates for 1990 through 2020 were obtained from data published on the National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data website (EPA 2021a). For Table 7-50, NEI reported emissions of CO, NO_x, SO_2, and NMVOCs are recategorized from NEI Tier 1/Tier 2 source categories to those more closely aligned with IPCC categories, based on EPA (2022).[14] NEI Tier 1 emission categories related to the waste sector categories in this report include: Waste Disposal and Recycling (landfills; publicly owned treatment works; industrial wastewater; treatment, storage, and disposal facilities; and other). As described in detail in the NEI Technical Support Documentation (TSD) (EPA 2021b), emissions are estimated through a combination of emissions data submitted directly to the EPA by state, local, and tribal air agencies, as well as additional information added by the Agency from EPA emissions programs, such as the emission trading program, Toxics Release Inventory (TRI), and data collected during rule development or compliance testing.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020, which are described in detail in the NEI's TSD (EPA 2021b). No quantitative estimates of uncertainty were calculated for this source category.

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[14] The NEI estimates and reports emissions from six criteria air pollutants (CAPs) and 187 hazardous air pollutants (HAPs) in support of National Ambient Air Quality Standards. Reported NEI emission estimates are grouped into 60 sectors and 15 Tier 1 source categories, which broadly cover similar source categories to those presented in this chapter. For this report, EPA has mapped and regrouped emissions of greenhouse gas precursors (CO, NO_x, SO_2, and NMVOCs) from NEI Tier 1/Tier 2 categories to better align with IPCC source categories, and to ensure consistency and completeness to the extent possible. See Annex 6.6 for more information on this mapping.

8. Other

The United States does not report any greenhouse gas emissions under the Intergovernmental Panel on Climate Change (IPCC) “Other” sector.

9. Recalculations and Improvements

Each year, many emission and sink estimates in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* are recalculated and revised, as efforts are made to improve the estimates through the use of better methods and/or data with the goal of improving inventory quality and reducing uncertainties, including the transparency, completeness, consistency, and overall usefulness of the report. In this effort, the United States follows the *2006 IPCC Guidelines* (IPCC 2006), which states, "Both methodological changes and refinements over time are an essential part of improving inventory quality. It is *good practice* to change or refine methods when available data have changed; the previously used method is not consistent with the IPCC guidelines for that category; a category has become key; the previously used method is insufficient to reflect mitigation activities in a transparent manner; the capacity for inventory preparation has increased; improved inventory methods become available; and/or for correction of errors."

In general, when methodological changes have been implemented, the previous Inventory's time series (i.e., 1990 to 2019) will be recalculated to reflect the change, per guidance in IPCC (2006). Changes in historical data are generally the result of changes in statistical data supplied by other agencies, and do not necessarily impact the entire time series.

The results of all methodological changes and historical data updates made in the current Inventory are presented in Figure 9-1, Table 9-1, and Table 9-2. Figure 9-1 presents the impact of recalculations by sector and on net total emissions across the timeseries. Table 9-1 summarizes the quantitative effect of all changes on U.S. greenhouse gas emissions by gas across the Energy, Industrial Processes and Product Use (IPPU), Agriculture, and Waste sectors, while Table 9-2 summarizes the quantitative effect of changes on annual net fluxes from Land Use, Land-Use Change, and Forestry (LULUCF). Both the figure and tables present results relative to the previously published Inventory (i.e., the 1990 to 2019 report) in units of million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.). To understand the details of any specific recalculation or methodological improvement, see the *Recalculations* within each source/sink categories' section found in Chapters 3 through 7 of this report. A discussion of Inventory improvements in response to review processes is described in Annex 8.

The Inventory includes new categories not included in the previous Inventory that improve completeness of the national estimates. Specifically, the current report includes methane (CH_4) emissions from post-meter uses (i.e., includes leak emissions from residential and commercial appliances, industrial facilities and power plants, and natural gas fueled vehicles), fugitive CO_2 emissions from coal mining, CO_2 emissions from land converted to flooded land, CH_4 emissions from land remaining and land converted to flooded land (i.e., reservoirs and other constructed waterbodies), and PFC (CF_4) emissions from electrical transmission and distribution.

The following source and sink categories underwent the most significant methodological and historical data changes, and all noted here are key categories except CO_2 emissions from incineration of waste. A brief summary of the recalculations and/or improvements undertaken are provided for these categories.

- *Natural Gas Systems (CH_4).* EPA received information and data related to the Inventory emission estimates through GHGRP reporting, the annual Inventory formal public notice periods, stakeholder feedback on updates under consideration, and new studies. EPA thoroughly evaluated relevant information available and made several updates to the Inventory, including incorporating post-meter emissions, reassessing the Gas STAR reductions data and incorporating Methane Challenge data, adding well blowout emissions, and using Pipeline and Hazardous Materials Safety Administration (PHMSA) data to update underground storage well counts. The recalculations and inclusion of post-meter estimates resulted in an average increase in CH_4 emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 13.2 MMT CO_2 Eq., or 8.1 percent.

- *Land Converted to Grassland (CO_2).* Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in *Forest Land Converted to Grassland,* and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. As a result, *Land Converted to Grassland* estimates increased an average of 2.9 MMT CO_2 Eq. (14.9 percent decrease in carbon stock change) on average over the time series.
- *Wastewater Treatment (N_2O).* EPA revised the domestic wastewater N_2O methodology based on the *2019 Refinement* (IPCC 2019) by updating the factor for non-consumed protein (1.13). EPA also revised the emission factor for centralized aerobic systems which affected 1990 through 2019 (ERG 2021a). All of these changes affected the time series from 1990 through 2019. Nitrous oxide emissions from wastewater treatment and discharge decreased an average 11.5 percent (2.6 MMT CO_2 Eq.) over the time series, with the smallest decrease of 10.0 percent (2.6 MMT CO_2 Eq.) in 2018 and largest decrease of 12.4 percent (3.1 MMT CO_2 Eq.) in 2015.
- *Manure Management (CH_4).* The manure management emission estimates include a number of revisions and methodology updates including: updated methodology for population distribution to states where USDA population data are withheld due to disclosure concerns (ERG 2021b) as well as raw animal population data (impacted poultry, sheep, and swine population estimates), revised MCF for pasture to align with updated guidance from IPCC (2019), and updated Cattle Enteric Fermentation Model (CEFM) output data. The cumulative effect of these recalculations led to an average decrease of 2.5 MMT CO_2 Eq. (5.0 percent) over the time series.
- *Incineration of Waste (CO_2).* Waste incineration estimates in the current Inventory were derived following a new methodology relying on different data sources than previously used. Specifically, waste tonnage estimates for 2006 through 2019 relied on several new data sources. For 1990 through 2020, CO_2 emissions were calculated with a new methodology using a carbon emission factor calculated from EPA's GHGRP data. The previous methodology relied on generation, disposal, and incineration rates of synthetic fibers, plastics, and synthetic rubber and the accompanying carbon contents to calculate CO_2 emissions for incineration of these materials. As a result of the changes in data and methodology, CO_2 emissions increased by an average of 2.1 MMT CO_2 Eq. (20.0 percent) each year over the time series.
- *Land Converted to Settlements (CO_2).* Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in Forest Land Converted to Settlements, and updated estimates for mineral and organic soils from 2016 to 2020 using the linear extrapolation method. As a result, emissions from Land Converted to Settlements decreased an average 2.0 MMT CO_2 Eq. (2.6 percent) over the time series.
- *Forest Land Remaining Forest Land (CO_2).* The methods used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes and harvested wood products (HWPs) from 1990 through 2020 are consistent with those used in the previous (1990 through 2019) Inventory. New national forest inventory (NFI) data in most states were incorporated in the latest Inventory which contributed to increases in forest land area estimates and carbon stocks. Fire data sources were also updated for Alaska through 2020 and this combined with the new NFI data for the years 2018 through 2020 resulted in substantial changes in carbon stocks and stock changes. Soil carbon stocks increased in the latest Inventory relative to the previous Inventory and this change can be attributed to refinements in the Digital General Soil Map of the United States (STATSGO2) dataset. This resulted in a structural change in the soil organic carbon estimates for mineral and organic soils across the entire time series. Additionally, recent land use change in AK (since 2015) also contributed to variability in soil carbon stocks and stock changes in recent years in the time series which contributed to differences in historic estimates. New HWP data suggest a continued decline in paper products in use over time due to changes in consumer

behavior (i.e., more use of electronic information sources) and a small drop in solid wood products in the last year due to a downturn in the economy associated with the global pandemic. Overall, these revisions lead to an average decrease of 2.0 MMT CO_2 Eq. (0.3 percent) across the time series.

- *Petroleum Systems (CH_4).* EPA received information and data related to the emission estimates through GHGRP reporting, stakeholder feedback on updates under consideration, and new studies. EPA did not make methodological updates for Petroleum Systems emission sources for this Inventory. However, for certain sources, changes in emissions were driven mainly by GHGRP data submission revisions and Enverus well count updates (Enverus 2021). The recalculations resulted in an average increase in CH_4 emission estimates across the 1990 through 2019 time series, compared to the previous Inventory, of 1.5 MMT CO_2 Eq. (3.6 percent).
- *Grassland Remaining Grassland (CO_2).* Recalculations are associated with updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method, in addition to a correction in the estimation of biomass C. The correction is associated with foliage estimates for woodlands that had been based on values for non-woodland foliage in the previous Inventory. The recalculations resulted in a decrease in emission estimates 1.4 MMT CO_2 Eq. (4.3 percent) on average over the time series compared to the previous Inventory.
- *Enteric Fermentation (CH_4).* In the previous Inventory, 1990 to 2017 estimates were retained from the 1990 through 2017 Inventory, and 2018 and 2019 estimates were based on a simplified approach that used emission factors and extrapolated population estimates for all animals. For the current Inventory, the Cattle Enteric Fermentation Model (CEFM) was used for cattle for all years, resulting in different estimates for 2018 and 2019 than the prior Inventory. For non-cattle livestock in the current Inventory, updated Tier 1 estimates were calculated for 2018 and 2019, yielding different results than the simplified approach used for these years in the prior Inventory. In addition, there were changes to cattle-related activity data including minor data revisions in the CEFM. Finally, non-cattle livestock emissions were impacted as a result of revisions to the USDA animal population data and how “other” populations were distributed to their respective states (ERGb 2021). The recalculations resulted in an average decrease in CH_4 emissions estimates across the 1990 through 2019 time series of 1.3 MMT CO_2 Eq. (0.7 percent).
- *Land Converted to Cropland (CO_2).* Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in Forest Land Converted to Cropland, and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. The recalculations resulted in an estimated C loss of 0.1 MMT CO_2 Eq. (1 percent) on average over the time series compared to the previous Inventory.

Figure 9-1 presents the impact of recalculations by sector and on net total emissions across the timeseries.

Figure 9-1: Impacts from Recalculations to U.S. Greenhouse Gas Emissions by Sector

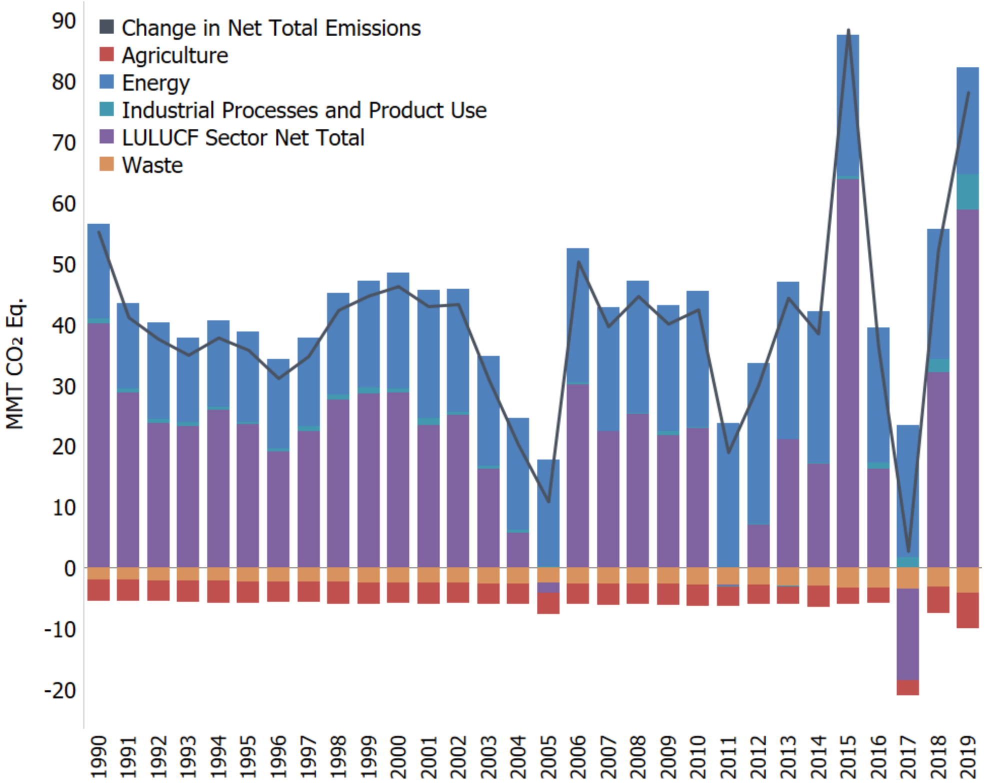

Table 9-1 and Table 9-2 present the quantitative impact of recalculations by gas for the Energy, IPPU, Agriculture, and Waste sources and for the Land Use, Land-Use Change, and Forestry sources and sinks, respectively.

Table 9-1: Revisions to U.S. Greenhouse Gas Emissions (MMT CO_2 Eq.)

Gas/Source	1990	2005	2016	2017	2018	2019	Average Annual Change
CO_2	**9.0**	**3.1**	**3.7**	**3.2**	**1.2**	**3.3**	**5.5**
Fossil Fuel Combustion	(0.3)	(1.5)	(1.9)	(1.2)	(2.1)	(4.4)	(0.7)
Electric Power Sector	NC	NC	+	+	+	0.1	+
Transportation	(0.2)	(0.1)	(2.2)	(2.5)	(3.8)	(3.5)	(0.6)
Industrial	(0.1)	(1.4)	0.2	0.3	0.5	(6.4)	(0.3)
Residential	NC	NC	+	+	0.2	4.6	0.2
Commercial	+	(+)	(+)	+	0.1	1.0	+
U.S. Territories	(+)	+	0.1	0.9	0.9	(0.3)	+
Non-Energy Use of Fuels	(0.6)	(0.2)	(0.3)	(0.9)	(0.9)	(2.0)	(0.6)
Natural Gas Systems	(0.1)	(0.2)	(0.3)	(0.1)	(1.5)	1.5	(0.1)
Cement Production	NC	NC	NC	NC	NC	NC	NC
Lime Production	NC	NC	NC	NC	NC	NC	NC
Other Process Uses of Carbonates	(0.1)	(0.2)	(0.2)	(0.1)	(0.1)	2.4	(0.1)
Glass Production	0.8	0.5	0.9	0.7	0.7	0.7	0.8
Soda Ash Production	NC	NC	NC	NC	NC	NC	NC
Carbon Dioxide Consumption	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	4.9	0.6	2.8	1.6	1.8	1.5	2.1
Titanium Dioxide Production	NC	NC	NC	NC	NC	NC	NC
Aluminum Production	NC	NC	NC	NC	NC	NC	NC

Iron and Steel Production & Metallurgical Coke Production	+	+	+	+	+	1.8	0.1
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Ammonia Production	NC	NC	NC	NC	NC	NC	NC
Urea Consumption for Non-Agricultural Purposes	NC	NC	0.2	0.2	0.2	(0.2)	+
Phosphoric Acid Production	NC	NC	NC	(+)	(+)	+	+
Petrochemical Production	NC	NC	(0.2)	(+)	NC	(0.1)	(+)
Carbide Production and Consumption	(0.1)	NC	NC	NC	NC	NC	(+)
Lead Production	NC	NC	NC	NC	NC	(+)	(+)
Zinc Production	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Petroleum Systems	(0.1)	(0.1)	0.1	+	0.2	(0.6)	(+)
Abandoned Oil and Gas Wells	(+)	(+)	(+)	(+)	(+)	+	(+)
Magnesium Production and Processing	0.1	+	+	+	+	+	0.1
Liming	NC	NC	NC	NC	NC	(+)	(+)
Urea Fertilization	NC	NC	(0.2)	(0.2)	(0.2)	(0.2)	(+)
Coal Mining	4.6*	4.2*	2.8*	3.1*	3.1*	3.0*	4.0*
International Bunker Fuels[a]	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Wood Biomass, Ethanol, and Biodiesel Consumption[b]	NC	NC	0.2	0.4	0.2	1.0	0.1
CH_4[c]	**3.9**	**11.3**	**15.2**	**15.4**	**15.2**	**9.1**	**10.7**
Stationary Combustion	+	(+)	+	+	+	0.1	+
Mobile Combustion	0.1	0.1	0.1	+	+	0.1	0.1
Coal Mining	NC	NC	NC	NC	NC	NC	+
Abandoned Underground Coal Mines	NC	NC	NC	NC	NC	NC	NC
Natural Gas Systems	8.5*	13.3*	17.9*	17.8*	19.2*	14.5*	13.2*
Petroleum Systems	(1.1)	1.9	1.2	1.2	1.3	1.3	1.5
Abandoned Oil and Gas Wells	(0.3)	(0.4)	(0.5)	(0.3)	(0.3)	0.4	(0.3)
Petrochemical Production	NC	NC	NC	NC	NC	(+)	(+)
Carbide Production and Consumption	(+)	NC	NC	NC	NC	NC	(+)
Iron and Steel Production & Metallurgical Coke Production	NC	NC	NC	NC	NC	NC	NC
Ferroalloy Production	NC	NC	NC	NC	NC	NC	NC
Enteric Fermentation	(1.2)	(1.3)	(0.9)	(0.9)	(2.3)	(2.4)	(1.3)
Manure Management	(2.3)	(2.6)	(2.5)	(2.4)	(2.3)	(3.7)	(2.5)
Rice Cultivation	NC	NC	(+)	(+)	(+)	+	+
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	NC
Landfills	NC	0.2	(0.1)	(0.2)	(0.4)	(0.9)	(+)
Wastewater Treatment	0.1	0.1	+	+	(0.1)	(0.3)	0.1
Composting	NC	+	+	+	+	+	+
Anaerobic Digestion at Biogas Facilities	+	(+)	NC	(+)	(+)	(+)	(+)
Incineration of Waste	NC	NC	+	+	+	+	+
International Bunker Fuels[a]	NC	NC	NC	NC	NC	NC	NC
N_2O[c]	**(2.2)**	**(2.5)**	**(1.6)**	**(1.7)**	**(1.5)**	**(0.3)**	**(2.1)**
Stationary Combustion	(+)	(+)	+	+	+	+	+
Mobile Combustion	(0.1)	(0.2)	0.3	0.3	0.3	2.0	0.1
Adipic Acid Production	NC	NC	0.1	0.1	0.2	(+)	+
Nitric Acid Production	NC	NC	NC	NC	NC	NC	NC
Manure Management	(0.1)	(0.1)	0.3	0.3	(0.2)	(0.1)	(+)
Agricultural Soil Management	0.1	0.4	0.7	0.7	0.7	0.6	0.4
Field Burning of Agricultural Residues	NC	NC	NC	NC	NC	NC	+
Wastewater Treatment	(2.1)	(2.7)	(3.1)	(3.2)	(2.6)	(3.0)	(2.6)
N_2O from Product Uses	NC	NC	NC	NC	NC	NC	NC
Caprolactam, Glyoxal, and Glyoxylic Acid Production	NC	NC	NC	NC	NC	NC	NC
Incineration of Waste	NC	NC	0.1	0.1	0.1	0.1	+

Composting	NC	+	+	+	+	+	+
Electronics Industry	NC	+	+	(+)	+	+	+
Natural Gas Systems	(+)	(+)	(+)	(+)	(+)	+	(+)
Petroleum Systems	(+)	(+)	(+)	(+)	(+)	(+)	(+)
International Bunker Fuels[a]	(+)	(+)	(+)	(+)	(+)	(+)	(+)
HFCs, PFCs, SF_6 and NF_3	**+**	**(0.1)**	**0.2**	**0.8**	**1.2**	**1.3**	**+**
HFCs	**+**	**(0.1)**	**0.2**	**0.8**	**1.3**	**1.3**	**+**
Substitution of Ozone Depleting Substances[d]	NC	(0.1)	0.2	0.8	1.3	1.3	+
HCFC-22 Production	NC	NC	NC	NC	NC	NC	(+)
Electronics Industry	+	+	+	+	+	+	+
Magnesium Production and Processing	NC	NC	NC	+	NC	NC	+
PFCs	**+**	**+**	**+**	**0.1**	**0.1**	**0.1**	**+**
Aluminum Production	NC	NC	+	+	(+)	(+)	+
Electronics Industry	+	+	+	0.1	0.1	0.1	+
Substitution of Ozone Depleting Substances[d]	NC	NC	NC	NC	NC	NC	NC
Electrical Transmission and Distribution	NO*	+*	+*	+*	NO*	+*	+*
SF_6	**+**	**+**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Electrical Transmission and Distribution	+	(+)	+	+	(0.1)	(+)	(+)
Electronics Industry	NC	+	(+)	(+)	+	(+)	+
Magnesium Production and Processing	NC	NC	(+)	NC	+	(+)	(+)
NF_3	**NC**	**NC**	**+**	**(+)**	**(+)**	**(+)**	**(+)**
Electronics Industry	NC	NC	+	(+)	(+)	(+)	(+)
Change in Total Gross Emissions (Sources)	**10.8**	**11.8**	**17.5**	**17.7**	**16.1**	**13.4**	**14.1**
Percent Change in Total Gross Emissions	**0.2%**	**0.2%**	**0.3%**	**0.3%**	**0.2%**	**0.2%**	**0.2%**

NC (No Change)

NO (Not Occurring)

+ Absolute value does not exceed 0.05 MMT CO_2 Eq. or 0.05 percent.

* Indicates inclusion of a new source for the current Inventory year that were not estimated in previous inventory. Emissions from new source categories and subcategories are captured in gross/net emissions and percent change totals.

[a] Emissions from International Bunker Fuels are not included in totals.

[b] Emissions from Wood Biomass, Ethanol, and Biodiesel Consumption are not included specifically in summing Energy sector totals. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for Land Use, Land-Use Change, and Forestry.

[c] LULUCF emissions of CH_4 and N_2O are reported separately from gross emissions totals in Table 9-2. LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; *Land Converted to Coastal Wetlands*; Land Remaining Flooded Land; Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[d] Small amounts of PFC emissions also result from this source.

Notes: Net change in total emissions presented without LULUCF. Totals may not sum due to independent rounding.

Table 9-2: Revisions to U.S. Greenhouse Gas Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2016	2017	2018	2019	Average Annual Change
Forest Land Remaining Forest Land	**16.2**	**(21.2)**	**(1.6)**	**(29.2)**	**17.7**	**43.7**	**2.8**
Changes in Forest Carbon Stocks[a]	13.6	(25.7)	(3.7)	(28.6)	21.5	57.0	2.0
Non-CO_2 Emissions from Forest Fires[b]	2.7	4.6	2.1	(0.6)	(3.8)	(13.3)	0.8
N_2O Emissions from Forest Soils[c]	NC	NC	NC	NC	NC	NC	NC
Non-CO_2 Emissions from Drained Organic Soils[d]	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Land Converted to Forest Land	**(0.4)**	**(0.4)**	**(0.4)**	**(0.4)**	**(0.4)**	**(0.4)**	**(0.4)**

Changes in Forest Carbon Stocks[e]	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Cropland Remaining Cropland	**NC**	**NC**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Changes in Mineral and Organic Soil Carbon Stocks	NC	NC	(+)	(+)	(+)	(+)	(+)
Land Converted to Cropland	**+**	**(0.1)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.1)**
Changes in all Ecosystem Carbon Stocks[f]	+	(0.1)	(0.3)	(0.3)	(0.3)	(0.3)	(0.1)
Grassland Remaining Grassland	**(1.4)**	**(1.3)**	**(1.8)**	**(2.0)**	**(2.0)**	**(2.1)**	**(1.4)**
Changes in Mineral and Organic Soil Carbon Stocks	(1.4)	(1.3)	(1.8)	(2.0)	(2.0)	(2.1)	(1.4)
Non-CO$_2$ Emissions from Grassland Fires[g]	NC	NC	NC	NC	NC	NC	NC
Land Converted to Grassland	**3.1**	**3.1**	**1.5**	**1.7**	**1.8**	**1.7**	**2.9**
Changes in all Ecosystem Carbon Stocks[f]	3.1	3.1	1.5	1.7	1.8	1.7	2.9
Wetlands Remaining Wetlands	**18.2**	**19.8**	**19.9**	**19.9**	**19.9**	**19.9**	**19.5**
Changes in Organic Soil Carbon Stocks in Peatlands	NC	NC	NC	NC	(+)	(+)	(+)
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	NC	NC	NC	NC	(+)	(+)	(+)
CH$_4$ Emissions from Coastal Wetlands Remaining Coastal Wetlands	+	(+)	NC	NC	NC	NC	(+)
N$_2$O Emissions from Coastal Wetlands Remaining Coastal Wetlands	NC	NC	NC	NC	NC	NC	NC
Non-CO$_2$ Emissions from Peatlands Remaining Peatlands	NC	NC	NC	+	+	+	+
CH$_4$ Emissions from Flooded Land Remaining Flooded Land	18.2*	19.8*	19.9*	19.9*	19.9*	19.9*	19.9*
Land Converted to Wetlands	**6.5**	**0.6**	**0.5**	**0.5**	**0.5**	**0.5**	**1.9**
Changes in Biomass, DOM, and Soil Carbon Stocks	(+)	+	+	+	+	+	+
CH$_4$ Emissions from Land Converted to Coastal Wetlands	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Changes in Land Converted to Flooded Land	3.9*	0.3*	0.3*	0.3*	0.3*	0.3*	0.3*
CH$_4$ Emissions from Land Converted to Flooded Land	2.6*	0.2*	0.2*	0.2*	0.2*	0.2*	0.2*
Settlements Remaining Settlements	**+**	**(+)**	**(+)**	**(4.0)**	**(3.7)**	**(2.9)**	**(0.4)**
Changes in Organic Soil Carbon Stocks	NC	NC	+	+	+	+	+
Changes in Settlement Tree Carbon Stocks	NC	NC	NC	NC	NC	NC	NC
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	+	(+)	+	(+)	(+)	+	+
N$_2$O Emissions from Settlement Soils[h]	NC	NC	(+)	(4.0)	(3.7)	(2.9)	(0.4)
Land Converted to Settlements	**(2.1)**	**(2.2)**	**(1.6)**	**(1.4)**	**(1.3)**	**(1.3)**	**(2.0)**
Changes in all Ecosystem Carbon Stocks[f]	(2.1)	(2.2)	(1.6)	(1.4)	(1.3)	(1.3)	(2.0)
Change in LULUCF Total Net Flux[i]	**16.7**	**(26.3)**	**(6.1)**	**(34.6)**	**15.9**	**51.9**	**1.8**
Change in LULUCF Emissions[j]	**23.5**	**24.6**	**22.2**	**19.5**	**16.3**	**6.9**	**21.0**
Change in LULUCF Sector Total[k]	**40.2**	**(1.8)**	**16.2**	**(15.1)**	**32.2**	**58.7**	**22.8**
Percent Change in LULUCF Total Net Flux	**4.5%**	**-0.2%**	**1.9%**	**4.0%**	**4.0%**	**7.4%**	**2.7%**

NC (No Change)

+ Absolute value does not exceed 0.05 MMT CO$_2$ Eq. or 0.05 percent.

* Indicates inclusion of a new source category or subcategory for the current Inventory year that were not estimated in the previous year. Emissions from new source categories and subcategories are captured in gross/net emissions and percent change totals.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools and harvested wood products.

[b] Estimates include CH$_4$ and N$_2$O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include N$_2$O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

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[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements, respectively. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements, respectively.

[g] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both Settlements Remaining Settlements and Land Converted to Settlements because it is not possible to separate the activity data at this time.

[i] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[j] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; *Land Converted to Coastal Wetlands*; emissions from Forest Soils and Settlement Soils; Flooded Land Remaining Flooded Land; and Land Converted to Flooded Land.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes.

Note: Totals may not sum due to independent rounding.

10. References and Abbreviations

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Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Air conditioner
ACC	American Chemistry Council
AEDT	FAA Aviation Environmental Design Tool
AEO	Annual Energy Outlook
AER	All-electric range
AF&PA	American Forest and Paper Association
AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFOLU	Agriculture, Forestry, and Other Land Use
AFV	Alternative fuel vehicle
AGA	American Gas Association
AGR	Acid gas removal
AHEF	Atmospheric and Health Effect Framework
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AIM Act	American Innovation and Manufacturing Act
AISI	American Iron and Steel Institute
ALU	Agriculture and Land Use
ANGA	American Natural Gas Alliance
ANL	Argonne National Laboratory
APC	American Plastics Council
API	American Petroleum Institute
APTA	American Public Transportation Association
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
ARI	Advanced Resources International
ARMA	Autoregressive moving-average
ARMS	Agricultural Resource Management Surveys
ASAE	American Society of Agricultural Engineers
ASLRRA	American Short-line and Regional Railroad Association
ASR	Annual Statistical Report
ASTM	American Society for Testing and Materials
AZR	American Zinc Recycling
BCEF	Biomass conversion and expansion factors
BEA	Bureau of Economic Analysis, U.S. Department of Commerce
BIER	Beverage Industry Environmental Roundtable
BLM	Bureau of Land Management
BoC	Bureau of Census
BOD	Biological oxygen demand
BOD5	Biochemical oxygen demand over a 5-day period
BOEM	Bureau of Ocean Energy Management
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOF	Basic oxygen furnace
BRS	Biennial Reporting System
BSEE	Bureau of Safety and Environmental Enforcement
BTS	Bureau of Transportation Statistics, U.S. Department of Transportation
Btu	British thermal unit
C	Carbon
C&D	Construction and demolition waste
C&EN	Chemical and Engineering News
CAAA	Clean Air Act Amendments of 1990
CAFOS	Concentrated Animal Feeding Operations
CaO	Calcium oxide
CAPP	Canadian Association of Petroleum Producers
CARB	California Air Resources Board
CBI	Confidential business information
C-CAP	Coastal Change Analysis Program
CDAT	Chemical Data Access Tool
CEAP	USDA-NRCS Conservation Effects Assessment Program
CEFM	Cattle Enteric Fermentation Model
CEMS	Continuous emission monitoring system
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CH_4	Methane
CHAPA	California Health and Productivity Audit
CHP	Combined heat and power
CI	Confidence interval
CIGRE	International Council on Large Electric Systems

CKD	Cement kiln dust
CLE	Crown Light Exposure
CMA	Chemical Manufacturer's Association
CMM	Coal mine methane
CMOP	Coalbed Methane Outreach Program
CMR	Chemical Market Reporter
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
COGCC	Colorado Oil and Gas Conservation Commission
CONUS	Continental United States
CRF	Common Reporting Format
CRM	Component ratio method
CRP	Conservation Reserve Program
CSRA	Carbon Sequestration Rural Appraisals
CTIC	Conservation Technology Information Center
CVD	Chemical vapor deposition
CWNS	Clean Watershed Needs Survey
d.b.h	Diameter breast height
DE	Digestible energy
DESC	Defense Energy Support Center-DoD's Defense Logistics Agency
DFAMS	Defense Fuels Automated Management System
DGGS	Division of Geological & Geophysical Surveys
DHS	Department of Homeland Security
DLA	DoD's Defense Logistics Agency
DM	Dry matter
DOC	Degradable organic carbon
DOC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	Dead organic matter
DOT	U.S. Department of Transportation
DRE	Destruction or removal efficiencies
DRI	Direct Reduced Iron
EAF	Electric arc furnace
EDB	Aircraft Engine Emissions Databank
EDF	Environmental Defense Fund
EER	Energy economy ratio
EF	Emission factor
EFMA	European Fertilizer Manufacturers Association
EJ	Exajoule
EGR	Exhaust gas recirculation
EGU	Electric generating unit
EIA	Energy Information Administration, U.S. Department of Energy
EIIP	Emissions Inventory Improvement Program
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EREF	Environment Research & Education Foundation
ERS	Economic Research Service
ETMS	Enhanced Traffic Management System
EV	Electric vehicle
EVI	Enhanced Vegetation Index
FAA	Federal Aviation Administration
FAO	Food and Agricultural Organization
FAOSTAT	Food and Agricultural Organization database
FAS	Fuels Automated System
FCCC	Framework Convention on Climate Change
FEB	Fiber Economics Bureau
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FGD	Flue gas desulfurization
FHWA	Federal Highway Administration
FIA	Forest Inventory and Analysis
FIADB	Forest Inventory and Analysis Database
FIPR	Florida Institute of Phosphate Research
FOD	First order decay
FOEN	Federal Office for the Environment
FOKS	Fuel Oil and Kerosene Sales
FQSV	First-quarter of silicon volume
FSA	Farm Service Agency
FTP	Federal Test Procedure
g	Gram
G&B	Gathering and boosting
GaAs	Gallium arsenide
GCV	Gross calorific value
GDP	Gross domestic product
GEI	Gulfwide Emissions Inventory
GHG	Greenhouse gas
GHGRP	EPA's Greenhouse Gas Reporting Program
GIS	Geographic Information Systems
GJ	Gigajoule
GOADS	Gulf Offshore Activity Data System
GOM	Gulf of Mexico
GPG	Good Practice Guidance
GRI	Gas Research Institute
GSAM	Gas Systems Analysis Model
GTI	Gas Technology Institute
GWP	Global warming potential
ha	Hectare
HBFC	Hydrobromofluorocarbon
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HDDV	Heavy duty diesel vehicle
HDGV	Heavy duty gas vehicle
HDPE	High density polyethylene
HF	Hydraulically fractured
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HFE	Hydrofluoroether
HHV	Higher Heating Value
HMA	Hot Mix Asphalt
HMIWI	Hospital/medical/infectious waste incinerator
HTF	Heat Transfer Fluid
HTS	Harmonized Tariff Schedule
HVAE	High Voltage Anode Effects
HWP	Harvested wood product
IBF	International bunker fuels

IC	Integrated Circuit
ICAO	International Civil Aviation Organization
ICBA	International Carbon Black Association
ICE	Internal combustion engine
ICR	Information Collection Request
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IGES	Institute of Global Environmental Strategies
IISRP	International Institute of Synthetic Rubber Products
ILENR	Illinois Department of Energy and Natural Resources
IMO	International Maritime Organization
IPAA	Independent Petroleum Association of America
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
ITC	U.S. International Trade Commission
ITRS	International Technology Roadmap for Semiconductors
JWR	Jim Walters Resources
KCA	Key category analysis
kg	Kilogram
kt	Kiloton
kWh	Kilowatt hour
LDPE	Low density polyethylene
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emission vehicles
LFG	Landfill gas
LFGTE	Landfill gas-to-energy
LHV	Lower Heating Value
LKD	Lime kiln dust
LLDPE	Linear low density polyethylene
LMOP	EPA's Landfill Methane Outreach Program
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas(es)
LTO	Landing and take-off
LULUCF	Land Use, Land-Use Change, and Forestry
LVAE	Low Voltage Anode Effects
M&R	Metering and regulating
MARPOL	International Convention for the Prevention of Pollution from Ships
MC	Motorcycle
MCF	Methane conversion factor
MCL	Maximum Contaminant Levels
MCFD	Thousand cubic feet per day
MDI	Metered dose inhalers
MDP	Management and design practices
MECS	EIA Manufacturer's Energy Consumption Survey
MEMS	Micro-electromechanical systems
MER	Monthly Energy Review
MGO	Marine gas oil
MgO	Magnesium oxide
MJ	Megajoule
MLRA	Major Land Resource Area
mm	Millimeter
MMBtu	Million British thermal units
MMCF	Million cubic feet
MMCFD	Million cubic feet per day
MMS	Minerals Management Service
MMT	Million metric tons
MMTCE	Million metric tons carbon equivalent
MMT CO_2 Eq.	Million metric tons carbon dioxide equivalent
MODIS	Moderate Resolution Imaging Spectroradiometer
MoU	Memorandum of Understanding
MOVES	U.S. EPA's Motor Vehicle Emission Simulator model
MPG	Miles per gallon
MRLC	Multi-Resolution Land Characteristics Consortium
MRV	Monitoring, reporting, and verification
MSHA	Mine Safety and Health Administration
MSW	Municipal solid waste
MT	Metric ton
MTBE	Methyl Tertiary Butyl Ether
MTBS	Monitoring Trends in Burn Severity
MVAC	Motor vehicle air conditioning
MY	Model year
N_2O	Nitrous oxide
NA	Not applicable; Not available
NACWA	National Association of Clean Water Agencies
NAHMS	National Animal Health Monitoring System
NAICS	North American Industry Classification System
NAPAP	National Acid Precipitation and Assessment Program
NARR	North American Regional Reanalysis Product
NAS	National Academies of Sciences, Engineering, and Medicine
NASA	National Aeronautics and Space Administration
NASF	National Association of State Foresters
NASS	USDA's National Agriculture Statistics Service
NC	No change
NCASI	National Council of Air and Stream Improvement
NCV	Net calorific value
ND	No data
NE	Not estimated
NEH	National Engineering Handbook
NEI	National Emissions Inventory
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEU	Non-Energy Use
NEV	Neighborhood Electric Vehicle
NF_3	Nitrogen trifluoride
NFI	National forest inventory
NGL	Natural gas liquids
NID	National inventory of Dams
NIR	National Inventory Report

NLA	National Lime Association
NLCD	National Land Cover Dataset
NMOC	Non-methane organic compounds
NMVOC	Non-methane volatile organic compound
NMOG	Non-methane organic gas
NO	Not occurring
NO$_2$	Nitrogen dioxide
NO$_x$	Nitrogen oxides
NOAA	National Oceanic and Atmospheric Administration
NOF	Not on feed
NPDES	National Pollutant Discharge Elimination System
NPP	Net primary productivity
NPRA	National Petroleum and Refiners Association
NRBP	Northeast Regional Biomass Program
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NREL	National Renewable Energy Laboratory
NRI	National Resources Inventory
NSCEP	National Service Center for Environmental Publications
NSCR	Non-selective catalytic reduction
NSPS	New source performance standards
NWS	National Weather Service
OAG	Official Airline Guide
OAP	EPA Office of Atmospheric Programs
OAQPS	EPA Office of Air Quality Planning and Standards
ODP	Ozone depleting potential
ODS	Ozone depleting substances
OECD	Organization of Economic Co-operation and Development
OEM	Original equipment manufacturers
OGJ	Oil & Gas Journal
OGOR	Oil and Gas Operations Reports
OH	Hydroxyl radical
OMS	EPA Office of Mobile Sources
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OTA	Office of Technology Assessment
OTAQ	EPA Office of Transportation and Air Quality
OVS	Offset verification statement
PADUS	Protected Areas Database of the United States
PAH	Polycyclic aromatic hydrocarbons
PCA	Portland Cement Association
PCC	Precipitate calcium carbonate
PDF	Probability Density Function
PECVD	Plasma enhanced chemical vapor deposition
PET	Polyethylene terephthalate
PET	Potential evapotranspiration
PEVM	PFC Emissions Vintage Model
PFC	Perfluorocarbon
PFPE	Perfluoropolyether
PHEV	Plug-in hybrid vehicles
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Productivity index
PLS	Pregnant liquor solution
POTW	Publicly Owned Treatment Works
ppbv	Parts per billion (10^9) by volume
ppm	Parts per million
ppmv	Parts per million (10^6) by volume
pptv	Parts per trillion (10^{12}) by volume
PRCI	Pipeline Research Council International
PRP	Pasture/Range/Paddock
PS	Polystyrene
PSU	Primary Sample Unit
PU	Polyurethane
PVC	Polyvinyl chloride
PV	Photovoltaic
QA/QC	Quality Assurance and Quality Control
QBtu	Quadrillion Btu
R&D	Research and Development
RECs	Reduced Emissions Completions
RCRA	Resource Conservation and Recovery Act
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RMA	Rubber Manufacturers' Association
RPA	Resources Planning Act
RTO	Regression-through-the-origin
SAE	Society of Automotive Engineers
SAGE	System for assessing Aviation's Global Emissions
SAIC	Science Applications International Corporation
SAN	Styrene Acrylonitrile
SAR	IPCC Second Assessment Report
SCR	Selective catalytic reduction
SCSE	South central and southeastern coastal
SDR	Steel dust recycling
SEC	Securities and Exchange Commission
SEMI	Semiconductor Equipment and Materials Industry
SF$_6$	Sulfur hexafluoride
SIA	Semiconductor Industry Association
SiC	Silicon carbide
SICAS	Semiconductor International Capacity Statistics
SNAP	Significant New Alternative Policy Program
SNG	Synthetic natural gas
SO$_2$	Sulfur dioxide
SOC	Soil Organic Carbon
SOG	State of Garbage survey
SOHIO	Standard Oil Company of Ohio
SSURGO	Soil Survey Geographic Database
STMC	Scrap Tire Management Council
SULEV	Super Ultra Low Emissions Vehicle
SWANA	Solid Waste Association of North America
SWDS	Solid waste disposal sites
SWICS	Solid Waste Industry for Climate Solutions
TA	Treated anaerobically (wastewater)
TAM	Typical animal mass
TAME	Tertiary amyl methyl ether
TAR	IPCC Third Assessment Report
TBtu	Trillion Btu
TDN	Total digestible nutrients

TEDB	Transportation Energy Data Book
TFI	The Fertilizer Institute
TIGER	Topologically Integrated Geographic Encoding and Referencing survey
TJ	Terajoule
TLEV	Traditional low emissions vehicle
TMLA	Total Manufactured Layer Area
TOW	Total organics in wastewater
TPO	Timber Product Output
TRI	Toxic Release Inventory
TSDF	Hazardous waste treatment, storage, and disposal facility
TTB	Tax and Trade Bureau
TVA	Tennessee Valley Authority
UAN	Urea ammonium nitrate
UDI	Utility Data Institute
UFORE	U.S. Forest Service’s Urban Forest Effects model
UG	Underground (coal mining)
U.S.	United States
U.S. ITC	United States International Trade Commission
UEP	United Egg Producers
ULEV	Ultra low emission vehicle
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAA	U.S. Aluminum Association
USAF	United States Air Force
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
USITC	U.S. International Trade Commission
VAIP	EPA’s Voluntary Aluminum Industrial Partnership
VAM	Ventilation air methane
VKT	Vehicle kilometers traveled
VMT	Vehicle miles traveled
VOCs	Volatile organic compounds
VS	Volatile solids
WBJ	Waste Business Journal
WEF	Water Environment Federation
WERF	Water Environment Research Federation
WFF	World Fab Forecast (previously WFW, World Fab Watch)
WGC	World Gas Conference
WIP	Waste-in-place
WMO	World Meteorological Organization
WMS	Waste management systems
WRRF	Water resource recovery facilities
WTE	Waste-to-energy
WW	Wastewater
WWTP	Wastewater treatment plant
ZEVs	Zero emissions vehicles