What hatchery capacity would be needed to support surfclam fishery mitigation via seeding fishing grounds?

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Summary

The high demand for renewable energy has stimulated the development of offshore wind farms along the east coast of the United States. Over two million acres are currently leased for the development of offshore wind turbines in U.S. waters (BOEM, 2022). It is expected that the Atlantic surf clam industry will be negatively impacted due to overlap between commercial fishing grounds and wind lease areas. This project explores the economic viability of a large-scale surf clam hatchery to offset additional costs, reduced revenues, and potential job losses associated with the displacement of the fishing fleet. Reports and primary literature were used to understand growth and survival of Atlantic surf clams in hatchery and nursery settings. This information was then applied to back-calculate the scale of hatchery efforts needed to support one-million bushels of fishery-sized clams (>120mm). Information on labor, energy, construction, and material inputs and costs for surf clams were gathered by analyzing literature and by meeting with hatchery managers, researchers, and others knowledgeable about shellfish hatchery production. A techno-economic cost model and Monte Carlo analyses were employed to explore the variability of costs. The analysis suggests that 374M to 2.1B clams are needed at the end of the hatchery stage to produce one-million bushels of market-sized surf clam. The calculated hatchery costs range from \$2.8M - \$13.3M and nursery costs range from \$800K-\$1.8M, with total production costs ranging from \$3.6M to \$15.1M. Under current market conditions where surf clams regularly sell for \$14-\$17/bushel, this analysis suggests that a large-scale hatchery could be a viable mitigation method.

1.0 Introduction

The U.S. east coast has leased over 1.7 million acres of federal ocean bottom for development of offshore wind energy projects, with plans for more than 1,500 foundations to be placed. These wind farms will reduce access for surfclam fishers to catch clams within turbine arrays, some of which overlap with important clam fishing grounds. Mitigation of these lost fishing opportunities is an important priority for federal agencies who will require mitigation by the wind companies. Federal agencies are prioritizing mitigation strategies that support social, cultural, and ecological goals. One possible mitigation strategy is to produce surfclam seed in an aquaculture setting (hatcheries and nurseries) to be planted on fishing grounds to then grow out for later fishing. This mitigation strategy – production of clam seed to support and sustain fishing grounds - is of interest to federal and state managers and could be an important opportunity for maintaining viable fishing grounds for the fishery; however, the scale that would be required to produce sufficient seed is yet unknown. Likewise, the costs to support this activity at scale is also unknown. This information gap is addressed in this report. Herein, we compile best available knowledge about hatchery and nursery growth and survival and costs of production to estimate the scale that would be needed to support 1 million bushels of market size Atlantic surfclams (*Spisula solidissima)* per year for fishing by the commercial fishing fleet.

2.0 Clam survival and growth

Literature review

Reports and primary literature were reviewed to specify a range of values for surfclam survival, mortality, and growth in aquaculture settings (hatchery, nursery) and in natural habitats. In total 26 reports were identified and reviewed. From these reports, rearing methods, average duration of a given stage, growth information (approximate initial and final size, growth rate, and growth parameters (L_∞, K, t_0) and survival rates were recorded for the following surfclam stages: larval (veliger larvae to metamorphosis), hatchery (post-larval to ~12mm), nursery (to ~40mm), and ocean (grow out in the wild to a fishable size). For the purposes of summarizing growth and survival ranges for each stage, **reported observations of zero survival were excluded; however, many reports indicated that in some instances total losses (zero or near zero survival) of surfclams can occur at every stage**. In some cases, growth rate was calculated from shell lengths and time provided in studies using the following equation:

$$\text{Growth rate (mm d}^{-1}) = \text{ShellLength}_{time2} - \text{ShellLength}_{time1} / \Delta\text{time}$$

Additionally, in some instances, von Bertalanffy growth parameters provided in each study were used to estimate shell length at age. von Bertalanffy (1938):

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right)$$

Where L_t is the mean length at age t (mm), t is age (years), L_∞ is the theoretical asymptotic maximum length (mm), K is the growth coefficient (year^{-1}) and t_0 is the theoretical age (years) at which length is zero.

Estimate hatchery scale production

All available observations of surfclam growth and survival (average, maximum, and minimum) from the literature were assembled to estimate scales of production from spawning through to fishable size classes. This information was then applied to back-calculate the scale of the hatchery efforts needed to support annual plantings that would each generate 1 million bushels of market-sized clams (>120mm shell length). Data was collected to determine the number of clams required of the same length group to fill a bushel. Using this data for size groupings ranging from 100-160 (in 10mm length increments) a relationship was built to determine count of surfclams (in one length group) per bushel (y) and was calculated as:

$$y = 1338.9e^{-0.023x}$$

where x is the length group in mm of surfclams.

Studies and reports from surfclams in hatchery and nurseries provided estimates of growth and survival in the larval and nursery stages that were applied to those stages in our calculation. Studies that examined surfclams in the field provided conservative survival estimates that were applied to the surfclams in their first year after moving from the nursery to the ocean. This cautious approach may underestimate survival of surfclams at theses sizes; however, our intent was to account for potential mortality associated with moving the surfclam seed and any initial predation experienced by stressed clams in their new ocean environment. For the second year in the ocean, a survival value was applied that was intermediate between the conservative first year value and the minimum, average, and maximum survival for adult clams based on Weinberg (1999). Subsequent years were assigned the observed minimum, average, and maximum adult survival for years three through five. By year five, we assumed the clams reach fishable sizes based on growth rates identified. The number of clams required at each stage informed the scale of the costs of production.

Across all the studies reviewed, gear type, study duration, and environmental variables varied, and thus generate a range of growth and survival estimates (Figure 1; S1-S5). Likewise, growth and survival varied across stages (larval, hatchery, nursery, and ocean) (S1-S5), and in some cases a given study provided more than one estimate of growth or survival for a given stage leading to unequal observations for each stage. Under average growing conditions, surfclams would complete the aquaculture (larval, hatchery and nursery) stages and reach 41 mm in approximately one year and enter the ocean in growth year two (Figure 1).

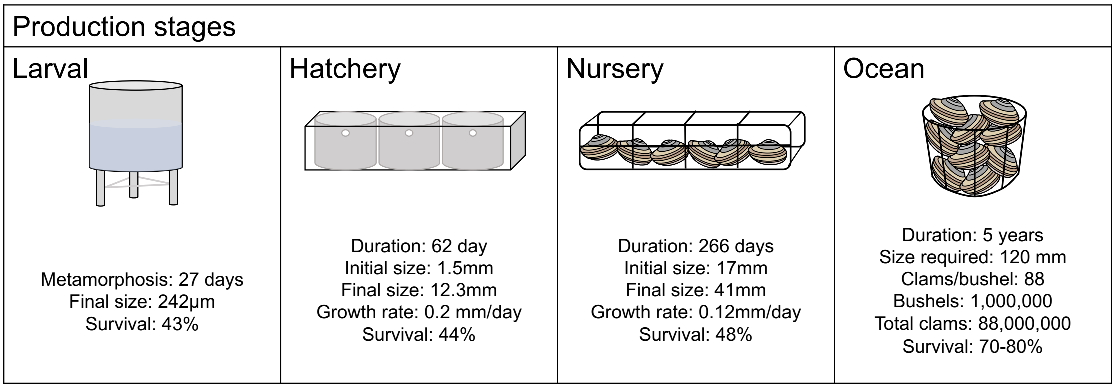

Figure 1: Average duration, size, and survival of each production stage (larval, hatchery, nursery) to reach the target 1M bushels of fishable surfclams (>120mm). Production of surfclam in the aquaculture settings (larval, hatchery, nursery) takes on average 355 days. Surfclams then need to remain in the ocean for 5 years to reach their target fishable size. All stages would require a total of 6 years.

Using the size relationship built to determine surfclam count per bushel it was determined that it would require 88 surfclams at 120mm to fill a bushel. Therefore, 88,000,000 market sized surfclams would be required to support 1 million bushels of market-sized clams. Using the average growth rates identified from the literature, three survival scenarios were applied as back calculations to determine the number of surfclams required at each stage to support one million bushels of market sized (>120mm) surfclams (Figure 2A).

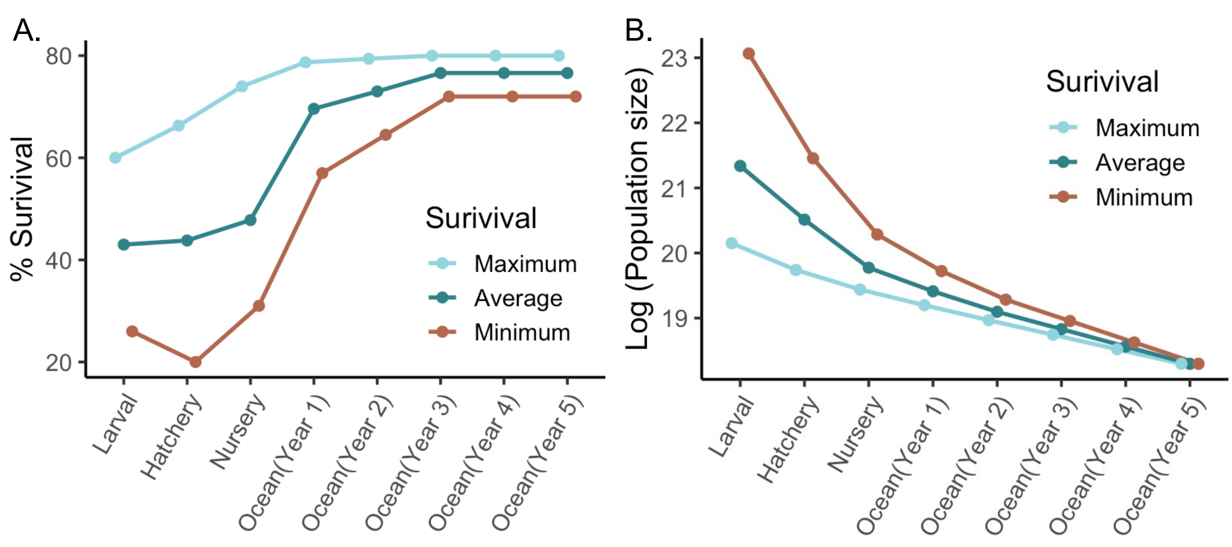

Figure 2: Three survival scenarios (maximum, average, and minimum) calculated from the literature for the aquaculture settings (larval, hatchery, nursery) and in natural setting. A. Percent survival for each scenario B. Change in cohort size under each survival scenarios.

3.0 Cost of production

Cost Estimates

Data on costs, production scales for variable production inputs, and product lifespans for materials were gathered by analyzing primary literature on hatchery and nursery production and by meeting with hatchery managers, researchers, and others knowledgeable about shellfish hatchery production. Individual cost items were grouped into the following categories: algae production, electricity, filtration, hatchery construction, labor and labor benefits, larval production, nursery production, and scientific instruments. All costs were specified as fixed or variable at the individual hatchery or nursery level, with variable costs scaling by hatchery or nursery output and fixed costs remaining constant for an individual hatchery or nursery. Hatcheries and nurseries were assumed to have maximum annual production of 120M and 100M surfclams, respectively. While all variable costs were scaled to 1M surfclams, fixed costs were scaled based on the number of required hatcheries and nurseries.

To determine the variable costs per one million seed for a particular cost item, the cost was divided by an estimate of maximum production scale for that item and then multiplied by one million. When the maximum production scale spanned a range of values, the cost would be averaged over that range. Annual maintenance costs were determined by taking the total cost of a given item and dividing by an estimate of the product's lifespan. Maintenance costs for variable inputs were scaled by output level using maximum production values as previously described. For all items, lower and upper bound cost estimates were based on available information. In instances where only one cost value was available, lower and upper bounds were constructed as +/- 25% of the value.

Construction

Available data on commercial construction costs per square foot were used to estimate the cost to construct a 20,000 square foot building to house each hatchery. Hatcheries require several unique design specifications, which were accounted for by increasing upper and lower bound construction costs by 20% (Airlite Plastics Company and Fox Blocks, 2022). Leasing space for hatchery production was considered but determined to be more expensive over the time horizon of the project. A shellfish hatchery blueprint, provided by the Virginia Institute of Marine Science (VIMS), was used to estimate costs for a hatchery piping and pump system. The blueprints provided a list of piping requirements that were used to determine the cost of metal and PVC piping required for the hatchery. The piping and pump system is used to move water in, out, and around the building efficiently. It was assumed each hatchery would be near a water source with appropriate salinity levels.

Filtration

Filters and filtration systems that are used in shellfish hatcheries were split into two categories: algal filtration and larval filtration. Algal filtration materials include bag filters, cartridge filters, bioreactor filters, and microfilters. Larval filtration materials include drum filters, disk filters, and sand filters. Low and high-cost estimates reflect a range of potential filtration systems that could be used, though typically hatcheries employ a subset of those filtration materials listed.

Algae Costs

Costs associated with purchasing bottled algae and culturing algae in the hatchery were both considered. Bottled algae costs were found from supplier websites. To calculate how many algal cells would need to be purchased or produced for different levels of hatchery output, the average daily feeding requirements for surfclams were estimated from published feeding rates for various larval and broodstock stages of hard clam (Hadley and Whetstone 2007). Due to limited data on surfclam feeding rates, published information on hard clams were used for comparison as feeding rates are similar. Feeding rates change as larvae and post-set clams grow, and we scaled feeding requirements according to Hadley and Whetstone (see supplementary material). The daily average feed rate (days 1-49) was approximately 421K algal cells per surfclam (Hadley and Whetstone 2007). This daily feed rate was then used to calculate how many larval clams could be fed from one 10L bottle of microalgae or one 250 L kalwall. By using a common algal density for bivalve aquaculture, estimated average daily feed rates, and the volume of one large kalwall, it was determined that one kalwall could support one day of feeding 2M clams. Therefore, the hatchery would need at least 10 large kalwalls to produce 20M surfclam seed per spawn. Additional algae production costs such has energy, filtration, and labor are included in separate cost categories.

Energy Requirements

Energy costs were approximated assuming energy requirements for a large-scale hatchery would be between those of a refrigerated warehouse, a non-refrigerated warehouse, and a commercial office building of comparable size. Annual energy cost estimates per kilowatt hour per square foot were extrapolated to an assumed hatchery footprint size of 20,000 square feet, which is approximately the size of research hatcheries at Rutgers and the Virginia Institute of Marine Science.

Labor

Labor requirements for different production scales were provided by hatchery and nursery managers. Labor costs were assessed by evaluating online job postings at various shellfish hatcheries and nurseries along the east and gulf coast of the United States. The job postings provided job descriptions and hourly and annual pay descriptions (see S6 for assumed pay scales). Each hatchery was assumed to require a hatchery manager, a bivalve hatchery technician, a full-time algae technician if culturing algae or a part time algae technician if purchasing bottled microalgae, and general or unskilled labor in an amount scaled to annual hatchery output. For nursery production, labor costs were scaled to output levels assuming one worker could split 50-70 bags per day. Assuming a stocking density of 3,000-4,000 clams per bag, it would take 4.2 days to split 1M surfclam seed

Costs associated with annual benefits for each job position were determined using the U.S. Bureau of Labor Statistics database, which indicated that median benefits of civilian workers were 47.5% of the original salary (U.S. Bureau of Labor Statistics, 2022). The additional benefits were added to the original salary to create annual costs per position.

Larval production, nursery production, and scientific instruments

Material costs associated with larval production included items for building upwellers and downwellers, along with various sized larval tanks to house larvae of different stages. These costs were considered variable based on the production scale of a hatchery. Fixed larval production costs included water pumping and heating systems and air blowers. Variable material costs for nursery production consisted of oyster bags and oyster cages, while fixed costs included a boat, floating dock, generator, pressure washer, and water pump. Each hatchery was assumed to have the following scientific instruments: a coulter counter, an autoclave, a centrifuge, and additional standard scientific equipment such as microscopes and thermometers.

Miscellaneous

Miscellaneous costs were included for the hatchery stage and the nursery stage to cover costs that may not have been included in the study. For hatchery production, we assumed annual miscellaneous costs of $50k per hatchery (i.e., per 120M seed leaving the hatchery stage) and for nursery production we assumed annual miscellaneous costs of $25k per nursery (i.e., per 100M seed leaving the nursery stage). Higher miscellaneous costs were assumed for hatchery production due to the relative complexity, high labor requirements, and increased use of materials during this production stage.

Monte Carlo Simulations

An annual cost function was constructed such that total hatchery and nursery production costs would depend on the level of output. Payments for construction, material, and other durable equipment expenses were annualized as:

$$A = \frac{(P * r)}{1 - (1 + r)^{-n}}$$

where the annual payment (A) depends on the loan amount (P), which would include hatchery construction and all physical assets need for hatchery or nursery operation, the interest rate (r), assumed to be 5%, and the length of the loan (n), assumed to be ten years.

Total annual costs were estimated as the sum of the annual payment for construction and materials, fixed and variable labor costs, energy costs, maintenance costs for fixed and variable material inputs, and miscellaneous costs. All variable costs, including variable material costs included in the total loan amount (P), increased linearly according to hatchery or nursery output. Fixed costs increased according to the required number of hatcheries and nurseries needed for a certain level of output (i.e., per 120M and 100M seed for hatcheries and nurseries, respectively).

For each cost item, 1,000 draws were taken from a uniform distribution bounded by low and high-cost estimates. Each of 1,000 cost vectors was then used to estimate a cost function and evaluate total annual and average costs over a range of annual seed output for hatcheries (1M to 3B) and nurseries (1M to 1B). Total annual costs under low, medium, and high survival scenarios were estimated using the cost function in conjunction with scenario-dependent production requirements.

Final Production Cost

Back calculations indicate that 374 million to 2.1 billion clams are needed at the end of the hatchery stage and 277 million to 645 million clams are needed at the end of the nursery stage to produce one-million bushels of fishable (120mm) surfclams (Figure 2B; Table 1). Hatchery costs associated with this level of output range from \$2.88M to \$13.25M, nursery costs range from \$0.81M to \$1.88M, and total costs range from \$3.68M to \$15.13M (Table 2). These ranges represent production from 4-18 hatcheries and 3-7 nurseries. Average costs were between \$6,000 and \$7,000 per 1M clams at the hatchery stage and approximately \$3,000 per 1M clams at the nursery stage. Uncertainty in total cost estimates increases at higher production levels as the number of required hatcheries and nurseries also increases (Figure 3). Total and average production costs were ~7% lower for hatchery production using bottled microalgae.

	Larval			Hatchery		Nursey		Ocean	
	Percent Survival	Initial population	Final population	Percent Survival	Final population	Percent Survival	Final population	Percent Survival	Final population
Maximum Survival	60%	940,000,000	564,000,000	66%	373,932,000	74%	276,709,680	Year 1: 78% Year 2: 79% Year 3: 80% Year 4: 80% Year 5: 80%	217,770,518 172,909,791 138,327,833 110,662,267 88,529,813
Average Survival	43%	4,300,000,000	1,849,000,000	44%	809,862,000	48%	387,114,036	Year 1: 70% Year 2: 73% Year 3: 77% Year 4: 77% Year 5: 77%	269,431,369 196,684,899 150,660,633 115,406,045 88,401,030
Minimum survival	26%	40,000,000,000	10,400,000,000	20%	2,080,000,000	31%	644,800,000	Year 1: 57% Year 2: 65% Year 3: 72% Year 4: 72% Year 5: 72%	367,536,000 237,060,720 170,683,718 122,892,277 88,482,440

Table 1: Required population size and anticipated survival (calculated from the literature) for each of the three survival scenarios (maximum, average, and minimum) for the aquaculture settings (larval, hatchery, nursery) and in natural setting.

	Hatchery		Nursery		Total	
	Cost (millions)	Std (millions)	Cost (millions)	Std (millions)	Cost (millions)	Std (millions)
Maximum Survival	$2.876	$0.222	$0.808	$0.081	$3.680	$0.234
Average Survival	$5.155	$0.389	$1.122	$0.113	$6.270	$0.401
Minimum survival	$13.254	$1.002	$1.882	$0.188	$15.131	$1.012

Table 2: Estimated cost range (in millions) of the hatchery and nursery stages for three survival scenarios (maximum, average, and minimum) to produce one million bushels of market-sized (>120mm) surfclams. Standard deviation (std) in cost for each stage is provided.

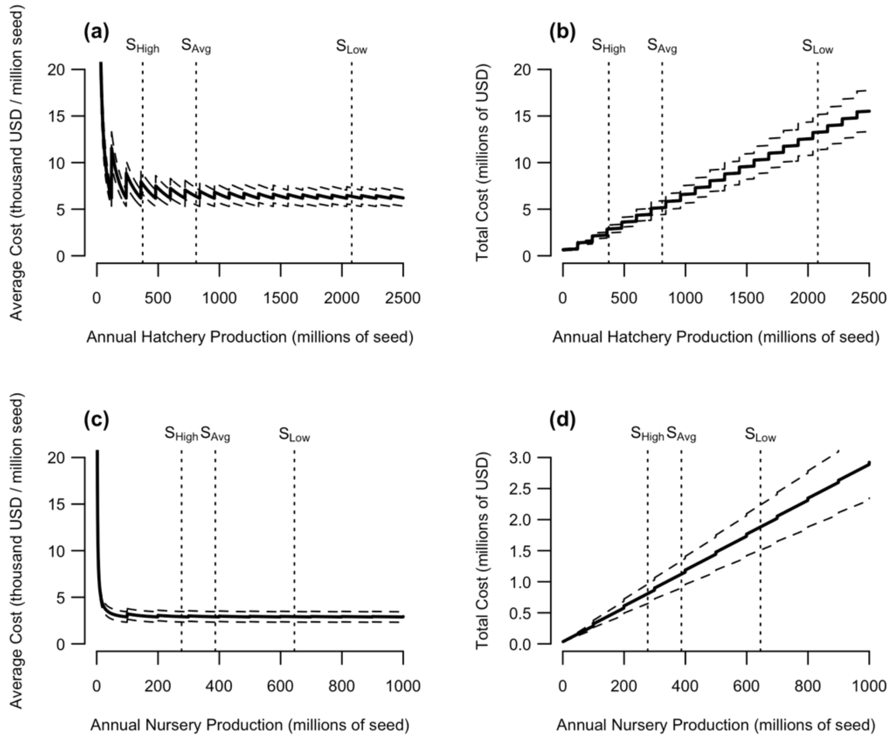

Figure 3: Average and total costs for annual hatchery and nursery production per million surfclams.

4.0 Summary

Across all shellfish species produced regionally (oysters, clams and scallops) there are 28 commercial/municipal shellfish hatchery/nurseries and 4 research hatchery/nurseries in the MidAtlantic (New York to Virginia). Expanding this region to Maine results in an increase to 37 commercial/municipal and 7 research (Rutgers Cooperative Extension, 2022). Many of these hatcheries and nurseries have relatively small capacity, supporting only single farms or a handful of farms. The level of effort estimated in this study therefore represents a considerable expansion of the contemporary hatchery and nursery production in the region. Given that this study considers this capacity to be dedicated to only one species, this represents a substantive undertaking relative to what already exists in the region.

Landings in the commercial surfclam fishery between 1995 to 2000 averaged 2.3 million bushels per year (NEFSC, 2017). Here, we are estimating the annual effort necessary to produce enough seed to result in 1 million bushels available to the fishery per year, which represents just over 43% of the contemporary landings. Ten percent of all commercial surfclam landings between 2015 to 2018, worth ~$2.2 million USD came from offshore wind lease areas based on data reported at NOAA's Socioeconomic Impacts of Atlantic Offshore Wind Development data portal (accessed

April 20, 2022). A recent study estimated that the revenue losses to the surfclam commercial sector due to displacement from fishing grounds by offshore wind energy range from 3 to 15% (Munroe et al, 2022; Scheld et al., 2022).

Under current market conditions where surfclams regularly sell for $14-$17/ bushel, this analysis suggests that a large-scale surfclam hatchery could be a viable mitigation method. Based off the given data, hatchery and production costs would not exceed sale revenues; however, **costs that are associated with land permitting, land acquisition, and ocean harvesting are not included** in this analysis.

A number of important caveats must be acknowledged when considering the results of this study. Several things were beyond the scope of this study and were excluded from the estimate presented. These results should be regarded as an underestimate of the true costs of producing sufficient surfclam seed to support 1 million bushels of commercial harvest. One important example, the cost of land acquisition and permitting, was not included as these costs would vary considerably based on where a facility is located and therefore could not be estimated. The costs of planting the seed in the ocean was also not included because the specifics of the planting location and methods have not yet been determined. Likewise, the costs and efficiencies associated with collecting (fishing for) the surfclams to recover them at the end of the study was also not included, yet it is understood that a dredge is not 100% efficient at catching clams. Thus, if a commercial vessel were to be used to collect (fish) the clams at the end of the grow out phase, it can be assumed that either the costs to recover all the clams planted would exceed typical fishing costs or some portion of the planted clams would remain in the ocean and not be caught. An alternative would be to produce extra surfclam seed to account for dredge inefficiencies; however, this would further increase the costs of production. Additionally, any incidental mortality incurred during collecting of the clams was not considered, and depending on the collection method, this might result in losses that warrant review.

Another important consideration that was not directly addressed in this study was availability of suitable lands and locations to accommodate the multiple hatcheries and nurseries that this study estimates would be needed. Hatchery and nursery facilities are typically located in areas adjacent to or very nearby the coastal ocean and often require certain water quality standards or other specific regulatory compliance that can add notable costs to aquaculture operations (van Senten et al., 2020). In the region considered here, the US MidAtlantic coastal states, waterfront property tends to be highly sought after and availability of lands adjacent to waters of the appropriate standards (salinity, temperature, sanitation) may be an impediment. We also did not expressly consider the availability and suitability of locations to which the seed clams produced would be planted. Given the vast areas over which the commercial fishery operates, there is a great deal of surfclam habitat along the MidAtlantic coast; however, how these locations could be permitted or leased for planting, how the planting would occur to minimize predatory losses, and how these areas would be managed in terms of fishery access during the growing years was not accounted for in this study.

Finally, in estimating maximum and minimum survival in hatchery, nursery, and ocean conditions, we did not include reports of zero survival. The literature often fails to report circumstances of hatchery and nursery failures (Gray et al., 2022). It should be recognized that our estimate includes a minimum survival assumption each year as a worst-case scenario, yet a worst-case scenario would be total loss of a year class due to mortality. Thus, our estimates may over-represent the survival of the clams produced because zero survival is never assumed.

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Supplemental Material

Aquaculture Setting Growth and Survival Summary

Larval

	Size at metamorphosis (µm)	Treatment length (days)	% Survival
Average	242.1	26.4	43.1
Minimum	146	21	25.7
Maximum	285	35	59.9

Hatchery

	Initial size (mm)	Final size (mm)	Treatment length (days)	Growth rate (mm d^{-1})	% Survival
Average	1.5	12.3	57	0.2	43.8
Minimum	0.3	2	21	0.04	20
Maximum	2	18	139	0.57	66.3

Nursery

	Initial size (mm)	Final size (mm)	Treatment length (days)	Growth rate (mm d^{-1})	% Survival
Average	16.9	41	266	0.12	47.8
Minimum	6	24.7	117	0.04	31.1
Maximum	30.7	55	696	0.24	74

S1: Summary of growth rate and survival (average, minimum, and maximum) in the aquaculture setting from primary literature reviewed. Study details including surfclam size during each stage and duration of treatment are included. For more details on studies used to create summary table refer to S3-S5.

Ocean Setting Growth and Survival Summary

	Shell Length (mm)														
	Year 1	Year 1 %S	Year 2	Year 2 %S	Year 3	Year 3 %S	Year 4	Year 4 %S	Year 5	Year 5 %S	Year 6	Year 7	Year 8	Year 9	Year 10
Average	40.9	70	64.2	73	84.1	77	100.2	77	112.0	77	121.5	128.7	135.0	141.0	144.7
Minimum	19.5	57	30.8	65	54.9	72	74.3	72	89.8	72	98.5	100.3	103.4	113.1	115.5
Maximum	61	79	86.4	80	106.7	80	119.5	80	131.2	80	141	149.6	155.7	158.5	162.3

S2: Summary of growth rate and survival (%S) (average, minimum, and maximum) in the ocean from primary literature reviewed. For more details on studies used to create summary table refer to S6.

Larval

Reference	Size range at metamorphosis (μm)	Treatment length (days)	% Survival
Loosanoff & Davis (1963)	230-250	35 (14ºC); 19 (22ºC)	---
Goldberg (1989)	280	21	---
Hurley and Walker (1996)	146-196	27	43.3
Snelgrove, Grassle & Butman, 1998	215-285	22-35 (19.2 – 24.3ºC)	---
Acquafredda (2019)	---	16	42.8

S3: Details from the literature used to understand growth and survival for the larval aquaculture stage. Recorded details include size at metamorphosis, treatment length in days and percent survival.

Hatchery

Reference	Study details			Size (mm)		Treatment length (days)	Growth rate (mm d^{-1})	% Survival
	Method	Mesh size	Stocking density	Initial	Final			
Goldberg (1980)	Flowing system	10" PVC and Nitex screen	2000 clams/screen	0.3	18	42	0.42	--
Goldberg (1980)	Flowing system	10" PVC and Nitex screen	2000 clams/screen	3	15	21	0.57	--
Acquafredda (2019)	Upweller	600µm, 1000µm, 1500µm	Day 1:60.9 clams/cm^2 Day 14: 15.3 clams/cm^2 Day 28: 3.8 clams/cm^2	2	18	48	0.38	65
Acquafredda (2019)	Raceway	5 cm of substrate (sand)	Day 1:60.9 clams/cm^2 Day 14: 15.3 clams/cm^2 Day 28: 3.8 clams/cm^2	2	13	48	0.16	20
Acquafredda (2019)	Raceway	No substrate	Day 1:60.9 clams/cm^2 Day 14: 15.3 clams/cm^2 Day 28: 3.8 clams/cm^2	2	15	48	0.18	25
Acquafredda (2019)	Downweller, Upweller, Bell siphon	200µm	Day 1: 185 clams/cm^2 Day 21: 103 clams/cm^2	0.4	18	42	0.06	66.3
Acquafredda (2019)	Upweller	400µm, 600µm, 750µm, 1000µm	127 clams/cm^2 107 clams/cm^2 95 clams/cm^2 25 clams/cm^2	1.5	8.3	139	0.05	52
Acquafredda (2019)	Downweller, Upweller	PVC cylinder and Nitex screen (Downweller- 235 µm; Upweller- 500, 750 µm)	Downweller: 40clams/cm^2 Upweller: 9 clams/cm^2	0.7	2	32	0.04	28
Sawyer (2020)	Downweller, Upweller	Downweller, 210 µm screen	--	--	3.5	96	--	50

S4: Details from the literature used to understand growth and survival for the hatchery aquaculture stage. Recorded details include method used to rear surfclams, stocking densities, sizes (shell length) throughout the study, treatment duration, and growth rate and survival.

Nursery

Reference	Study details: Method	Mesh size	Stocking density	Size (mm): Initial	Final	Treatment length (days)	Growth rate (mm d^{-1})	% Survival
Goldberg (1980)	Laboratory, raceway	10 cm of substrate	100, 500 clams/m^2	18	55	152	0.24	74
Goldberg (1989)	Field, Cages	8mm wire mesh	500, 1000, 2000 clams/m^2	15.7	40	136	0.18	--
Goldberg (1989)	Field, Cages	8mm wire mesh	500 clams/m^2	30.7	50	117	0.17	--
Goldberg (1989)	Field, Cages	8mm wire mesh	500 clams/m^2	28	47	212	0.09	--
Goldberg and Walker (1990)	Field, Cages	8mm square opening	200 clams/cage	21.6	45.5	168	0.14	70.2
Goldberg and Walker (1990)	Field, Cages	8mm square opening	200 clams/cage	12.4	38.6	157	0.17	57.7
Goldberg and Walker (1990)	Laboratory, trays	Substrate (mud, sand, or mixture)	--	8.6	31	164	0.14	46.8
Davis et al. (1997)	Field, Sediment filled containers	--	329 clams/m^2	23	34	135	0.08	--
Acquafredda (2019)	Field	mesh bags (5mm, 9mm) – various methods tested	3400 clams/m^2	8.9	47	696	0.052	12
Sawyer (2020)	Field, Oyster bags	2, 6, 9mm	50/ft^2	6	27	462	0.05	41.9
Sawyer (2020)	Field, Florida bags	4, 10mm	50/ft^2	10	24.7	397	0.08	31.1
Sawyer (2020)	Field, Bottom plant	10mm	35/ft^2	19.3	52	401	0.04	9.8

S5: Details from the literature used to understand growth and survival for the nursery aquaculture stage. Recorded details include method used to grow out surfclams, stocking densities, sizes (shell length) throughout the study, treatment duration, and growth rate and survival. Values in red were identified as outliers and excluded from analysis.

Position	Fixed/Variable	Annual salary range
Algae Technician	Fixed	$90,000-$110,000
Part-time Algae Technician	Fixed	$45,000-$55,000
Bivalve Technician	Fixed	$75,000-85,000
Hatchery Manager	Fixed	$100,000-$120,000
Nursery Laborer	Variable	$800 - $1100
Unskilled Laborer	Fixed	$55,000-$65,000

S6: Annual salaries of hatchery and nursery laborers. Low and high annual salaries were based off job openings from online job boards along the east and gulf coast. Labor benefits of 47.5% are included in the salary estimates and were based off a median percentile for civilian workers (U.S. Bureau of Labor Statistics, 2022). To calculate the variable low and high annual salary for the nursery laborers, we assumed one laborer could split 70 bivalve bags per day per laborer for one million seed. The stocking density was assumed to be 3-4K seed surfclams (Sawyer 2020; Acquafredda, 2021), and the labor rare was used to estimate that splitting would take approximately 4.2 days. The rate to split one million seed and the low and high annual salary of the unskilled labor were used to calculate an approximate cost of $800-110 per laborer to split one million seed over 4.2 days.