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ORIGINAL ARTICLE

Hatchery capacity needed to support large-scale Atlantic surfclam fishery enhancement

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Abstract

Fishery enhancement methods are being explored globally to sustain commercial and recreational fisheries through improving the productivity and management of marine populations impacted by anthropogenic stressors. It is expected that access to important Atlantic surfclam fishing grounds will be limited or lost due to growing overlap with offshore wind energy development. This study explores the economic viability of large-scale hatchery production to improve fishery access and potentially 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 the growth and survival of Atlantic surfclams in hatchery and nursery settings to calculate the scale of hatchery efforts needed to support one million (1M) bushels of fishery-sized clams (>120 mm). Data on labour, energy, construction and material inputs and costs for hatchery and nursery production were gathered by analysing available literature and information provided by hatchery managers, researchers and others knowledgeable about shellfish hatchery production. A techno-economic cost model and Monte Carlo analyses were employed to explore average costs and their variability. This study suggests that 374M–2.1B Atlantic surfclams are needed at the end of the hatchery stage to produce 1M bushels of market-sized product. Total production costs range from $3.7 to $15.1M, including $2.9–$13.3M in hatchery costs and $800K–$1.9M in nursery costs. Under current market conditions, where Atlantic surfclams regularly sell for $14–$17/bushel, this analysis suggests that hatchery production could be considered a viable fishery enhancement method that supports human access to the fishery, though several additional questions remain.

KEYWORDS
Atlantic surfclam, hatchery production, ocean multi-use, techno-economic cost model

1 | INTRODUCTION

Fishery stock enhancement strategies, also known as restocking for conservation purposes, or sea ranching for economic purposes, have gained interest among the US stakeholders as challenges associated with food security, marine habitat degradation and potential job losses increase due to anthropogenic stressors (Taylor et al., 2017). These enhancement strategies are used broadly across various marine fish and shellfish populations, with intent to enhance the productivity and management of marine populations by addressing natural or human-induced ecological limitations, such as recruitment and habitat limitations and degraded natural habitats (Taylor et al., 2017). Global mariculture, the production of aquatic animals in an ocean setting for an entire life cycle or grow out stage only, was estimated to be 68.1 MT in 2020, consisting of aquatic animals (33.1 MT) and algae (35 MT) (FAO, 2022). Data from national reports estimate a large diversity of globally farmed aquatic species, consisting of 494 taxonomically recognized species, which include 313 species of finfish and 88 species of molluscs (FAO, 2022). However, this report cites that industry believes the real number of farmed aquatic species is much greater than the estimated total due to limitations in data processing and data collection, such as non-reporting countries. Fishery enhancement continues to improve through technical developments and advances in aquaculture and enhancement techniques, which has helped to improve the efficiency of hatchery production to support the goals of the impacted fisheries (Blount et al., 2017; Camp et al., 2017; Taylor et al., 2017). From 1990 to 2020, total world aquaculture has expanded by 609% in annual output, which has allowed for current day seafood production to become an almost 50/50 split of aquaculture and capture fisheries (FAO, 2022). However, the report is not clear to what extent fishery enhancement strategies have contributed to total global seafood production. By increasing and improving efforts for fishery enhancement, opportunities can continue to grow for recreational, commercial, artisanal and conservation stakeholders (Taylor et al., 2017); however, these benefits should be reconciled against the costs required for developing and supporting large-scale enhancement efforts.

The Atlantic surfclam (*Spisula solidissima*) is a large marine bivalve that is distributed from the Gulf of St. Lawrence, Canada to Cape Hatteras, North Carolina; however, the fishery for Atlantic surfclam is based off the Mid-Atlantic coast, where surfclams have historically been most abundant (National Oceanic and Atmospheric Administration [NOAA], 2023). According to the 2020 stock assessment, the Atlantic surfclam population is not overfished and overfishing is not occurring (NOAA, 2023). Hydraulic clam dredges, a large metal dredge dragged along the ocean floor via boat that relocates slurry (sediment and water mixture) via pipeline to collect clams more efficiently, are the typical harvest method in the commercial fishery, along with the occasional dredge and hand-harvest, whereas the recreational fishery is limited to hand-harvest (Munroe et al., 2023). Surfclam landings are typically used for human consumption, such as breaded clam strips or in prepared soups, whereas a small portion of product is used for bait. In 2021, the commercial Atlantic surfclam industry was valued at $24M with a total harvest of 12.5k MT (NOAA, 2023). The Atlantic surfclam is considered one of the most important commercial clam species that is harvested in the United States, specifically supporting valuable fisheries in the federal waters off New Jersey and New York (NOAA, 2023).

Along the US east coast, over 890,000 hectares of federal ocean bottom has been leased for the development of offshore wind energy projects (Bureau of Ocean Energy Management [BOEM], 2022), with more than 2000 turbine foundations anticipated to be constructed over the next 10 years (Bureau of Ocean Energy Management (BOEM), 2020). This development is expected to significantly impact commercial and recreational fisheries in the region, though considerable uncertainty remains regarding specific impact pathways and magnitudes (Gill et al., 2020; Methratta et al., 2020). The Atlantic surfclam fishery operates in and around areas leased for offshore wind development and has been identified as particularly vulnerable given the locations of fishing activity and key ports, as well as the use of specialized bottom dredge gear (Kirkpatrick et al., 2017). A bioeconomic agent-based simulation model was used to explore the potential economic impacts of offshore wind development on the Atlantic surfclam fishing industry, finding exclusion and displacement of fishing effort could lead to revenue losses of ~$1–5M annually for fishing vessels and $3–17M annually for the processing sector (Scheld et al., 2022). Furthermore, shifts in fishing activity were found to increase average operational costs for both harvesters and processors.

In Europe, where the offshore wind sector has grown steadily over the last two decades, fisheries mitigation strategies are varied, and the multi-uses of offshore wind energy sites are being increasingly explored (Buck & Langan, 2017; Schupp et al., 2021). Fishing within offshore wind farms remains rare however (Gill et al., 2020) and is not expected for the existing Atlantic surfclam fleet in the United States. In the United Kingdom, stock enhancement using hatchery-produced shellfish seed (juvenile shellfish) was considered in a study investigating fisheries mitigation alternatives associated with offshore wind development. It was noted that direct stock enhancement via hatchery production would be beneficial in minimizing disruption to fishing communities and providing long-term job security (Blyth-Skyrme, 2010). However, the viability of fisheries enhancement as a mitigation strategy has yet to be evaluated.

Several fisheries enhancement trials have been deemed unsuccessful and not economically viable due to high costs associated with hatchery production compared to market costs (Hilborn, 1998; Kitada, 2018). Ecological and genetic challenges associated with stock enhancement include substantial density-dependent growth, reduced growth rates of hatchery and wild-fish and changes in genetic composition from hatchery-reared animals to wild populations (Kitada, 2018). Furthermore, most studies on hatchery enhancement are at experimental stages, and very few studies have provided results on the effectiveness of hatchery enhancement at fishery production scales (Kitada, 2018). This research explored the viability of hatchery-supported stock enhancement of the Atlantic surfclam fishery at a large, fishery-relevant scale. The motivation for this project relates to the anticipated reduction in fishery access to wild Atlantic surfclam stock due to offshore wind development. Although stock enhancement is potentially desirable in that it helps to maintain existing fishing activities and related industries, the necessary scale and associated costs are unknown. Here, we compile the best available knowledge about hatchery and nursery growth and survival, as well as production costs, to estimate the scale that would be needed to support one million (1M) bushels of market-sized Atlantic surfclams per year for fishing by the commercial fishing fleet.

2 | MATERIALS AND METHODS

2.1 | Clam survival and growth

2.1.1 | Literature review

Reports and primary literature were reviewed to specify a range of values for surfclam survival, mortality and growth in aquaculture settings (larval, hatchery and nursery) and in natural habitats. Rearing methods, average duration at a given stage, growth information (approximate initial and final size), growth rate, growth parameters (L_∞, K and t_0) and survival rates were recorded for the following surfclam stages: larval (fertilization to metamorphosis), hatchery (post-larval to ~12 mm), nursery (to ~40 mm) and ocean (grow out in the wild to a fishable size). In some cases, growth rate was calculated from shell lengths and time provided in studies using the following equation:

$$\text{growthrate}(\text{mmd}^{-1}) = \text{shelllength}_{\text{time2}} - \text{shelllength}_{\text{time1}}/\Delta\text{time}. \quad (1)$$

Conversely, some studies provided growth parameters. If provided, these parameters were used to estimate shell length at age (von Bertalanffy, 1938):

$$L_t = L_\infty \; (1 - e^{-K(t - t_0)}), \quad (2)$$

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.

2.1.2 | 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 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 1M bushels of market-sized clams (>120 mm shell length), where 1 bushel is equal to 53.2 L or 5–7 kg of surfclam meat. Data were collected to determine the number of clams of a given size required to fill a bushel. A relationship was built to determine the count of surfclams (in one length group) per bushel.

Studies and reports from surfclams in hatcheries 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 the survival of surfclams at these 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 3–5. By year 5, it was assumed that clams were at fishable sizes based on growth rates identified. The number of clams required at each stage informed the scale of the costs of production.

2.2 | Cost of production

2.2.1 | Cost estimates

Data on costs, production scales for variable production inputs and product lifespans for materials were gathered by analysing primary literature on hatchery and nursery production and in meetings 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 labour and labour benefits, larval production, nursery production and scientific instruments. All costs are in US dollars and 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 a maximum annual production of 120 and 100M surfclams, respectively. Although 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 1M seed for a particular cost item, the cost was divided by an estimate of maximum production scale for that item and then multiplied by 1M. 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.

Cost estimates and model projections were based off a stylized model of hatchery and nursery production. Data were gathered from a wide range of hatchery and nursery systems throughout the US Atlantic and Gulf Coasts. The methods and materials used in hatchery and nursery production of bivalve shellfish are similar across species and geographic locations. Co-production of species was not considered but should be expected to affect the total output of surfclams. Cost estimates did not include the cost of land acquisition and permitting, planting seed in the ocean and later collection (i.e. fishing) or incidental mortality during harvest. Finally, transportation costs between hatchery and nursery were not included as it was assumed distance was minimal, which is common for shellfish hatcheries in the region.

2.2.2 | Construction

Available data on commercial construction costs per metre squared were used to estimate the cost to construct a ~1800 m^2 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 & Fox Blocks, 2022). Leasing space was considered but given the unique specifications of large-scale hatchery production, variability in lease rates and terms and the likely cost advantages of hatchery construction over the time horizon of this project, it was not thought to be a viable alternative. 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 and sanitary levels.

2.2.3 | 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.

2.2.4 | 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 brood stock stages of hard clam (Hadley & 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 Table S10). The daily average feed rate (days 1–49) was approximately 421k algal cells per surfclam (Hadley & Whetstone, 2007). This daily feed rate was then used to calculate how many larval clams could be fed from one 10 L 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 seeds per spawn. Additional algae production costs, such as energy, filtration, and labour, are included in separate cost categories.

2.2.5 | Energy requirements

Energy costs were approximated, assuming energy requirements for a large-scale hatchery would be among 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 metre squared were extrapolated to an assumed hatchery footprint size of ~1800 m^2, which is approximately the size of research hatcheries at Rutgers University and VIMS.

2.2.6 | Labour

Labour requirements for different production scales were provided by hatchery and nursery managers. Labour 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 Table 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 labour in an amount scaled to annual hatchery output. For nursery production, labour costs were scaled to output levels assuming one worker could split 50–70 bags per day. Assuming a stocking density of 3000–4000 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 (2022) database, which indicated that median benefits of civilian workers were 47.5% of the original salary. The additional benefits were added to the original salary to create annual costs per position.

2.2.7 | Hatchery 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. Larvae are produced from broodstock that were acquired from wild stocks via fishing vessels or hand collected. These costs were considered variable based on the production scale of a hatchery. Fixed larval production costs included water pumping, heating systems and air blowers. Variable material costs for nursery production consisted of mesh bags and cages, whereas 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 standard scientific equipment such as microscopes and thermometers.

2.2.8 | 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 labour requirements and increased use of materials during this production stage.

2.2.9 | Monte Carlo simulations

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

$$A = \frac{(P \cdot r)}{1-(1+r)^{-n}}, \tag{3}$$

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 10 years.

The loan amount (P) required for hatchery or nursery production was specified as

$$P = VMaterial \times seed + FMaterial \times \left[1 + floor\left(\frac{seed}{maxseed}\right)\right], \tag{4}$$

where *VMaterial* are variable material costs, *FMaterial* are fixed material costs, *seed* is the production level in millions of *seed* and *maxseed* specifies the maximum annual production of 120 or 100M for hatcheries or nurseries, respectively. The number of hatcheries or nurseries required for a particular output level, and thus the required loan amount to finance fixed material costs, was determined as one plus a floor function of the production level divided by maximum production per hatchery or nursery.

Total annual costs (TC) for hatchery or nursery production were formulated as

$$TC = (VLabour + VMaint) \times seed + (FLabour + FEnergy + FMaint + Misc) \times \left[1 + floor\left(\frac{seed}{maxseed}\right)\right] + A, \tag{5}$$

where *VLabour* are variable labour costs, *VMaint* are variable maintenance costs, *FLabour* are fixed labour costs, *FEnergy* are fixed energy costs, *FMaint* are fixed maintenance costs and *Misc* are fixed miscellaneous costs. Variable costs were scaled by seed production and fixed costs were scaled by the number of required hatcheries or nurseries.

For each cost item, 1000 draws were taken from a uniform distribution bounded by low- and high-cost estimates. Each of 1000 cost vectors was then used to calculate hatchery and nursery cost functions and evaluate total annual and average costs over a range of annual seed output (hatcheries from 1M to 3B and nurseries from 1M to 1B). Cost functions were used to calculate median annual costs and their standard deviation separately for hatcheries and nurseries under each survival scenario (low, medium and high) and associated seed production requirements, which were then summed together to assess total production costs.

3 | RESULTS

3.1 | Clam survival and growth

In total, 26 reports of surfclam growth and survival were identified and reviewed (Supporting Information). 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 occurred at every stage. 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; Tables S1–S5). Likewise, growth and survival varied across stages (larval, hatchery, nursery and ocean) (Tables 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 1 year and enter the ocean in growth year 2 (Figure 1).

A relationship was established, using data from animals ranging from 100 to 160 (in 10 mm length increments), 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. Using this relationship which determined surfclam count per bushel, 88 surfclams at 120 mm are required to fill a bushel. Therefore, 88,000,000 market-sized surfclams would be required to support 1M 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 1M bushels of market-sized (>120 mm) surfclams (Figure 2a).

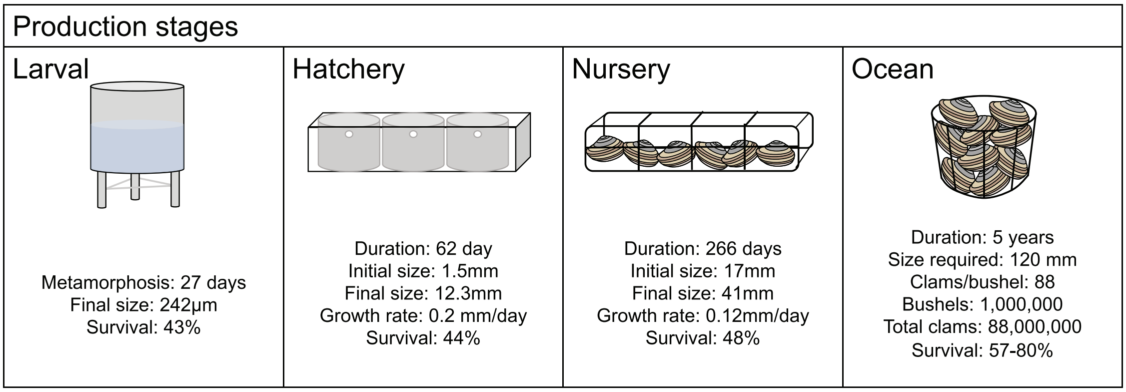

FIGURE 1 Average duration, size and survival of each production stage (larval, hatchery and nursery) to reach the target one million (1M) bushels of fishable surf clams (>120 mm). Production of surfclam in the aquaculture settings (larval, hatchery and nursery) takes on average 355 days. Surfclams then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

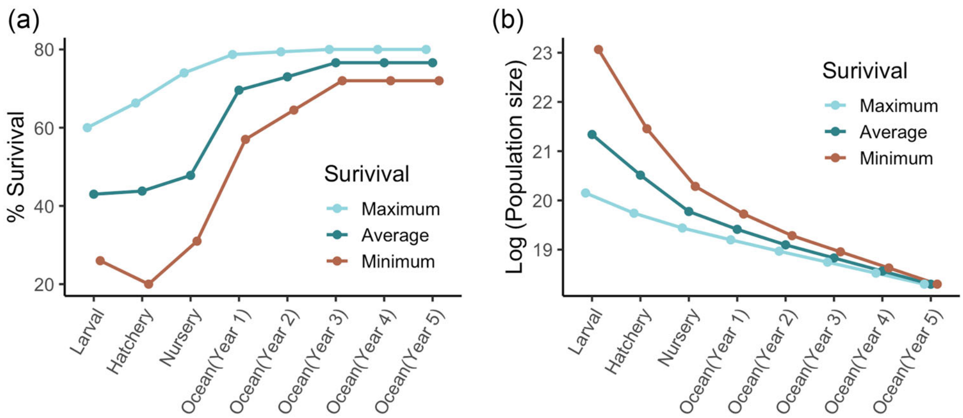

FIGURE 2 Three survival scenarios (maximum, average and minimum) calculated from the literature for the aquaculture settings (larval, hatchery and nursery) and in natural setting: (a) per cent survival for each scenario; (b) change in cohort size under each survival scenarios.

3.2 | Cost of production

In total, 64 references (primary and grey literature, websites and personal communications) were utilized in assessing hatchery and nursery production costs (Table S7). We identified 61 cost categories from 60 sources and estimated cost ranges for 36 fixed (one-time and annual) and 25 variable (per 1M seed) production inputs (Table S8). Maintenance costs were estimated based upon material lifespans, which averaged 15.48 years across all materials.

Fixed, variable and maintenance costs were evaluated by cost category. For variable inputs, the lowest non-zero costs were for scientific instruments ($2.16/M seed/year, Figure 3, Table S9), and the highest was for nursery labour ($950.78/M seed/year, Figure 3, Table S9). For fixed costs, materials needed for algae production were the lowest ($247.63/year, Figure 3, Table S9) and hatchery labour costs for algae production were the highest ($289,813.39, Figure 3, Table S9). Variable annual maintenance costs were low overall, with the exception of nursery materials ($817.83/M seed/year, Table S9). Fixed annual maintenance costs were considerably more expensive, with the highest costs being building maintenance (i.e. maintenance related to construction) ($51,341.01/year, Table S9) and the lowest costs being maintenance associated with algae production at ($204.36/year, Table S9). The difference in cost between algae culture and purchasing bottled algae feed arose because algae culture required higher fixed costs, specifically materials (e.g. tanks, feed system and chemostat system) and labour, whereas bottled algae feed had higher variable costs. For a hatchery and nursery operating at full capacity (120M annual output for a hatchery), variable costs, including variable maintenance costs, were approximately 40% of annual total costs.

3.3 | Total production costs

Estimates based on clam growth and survival indicated that 374M to 2.1B clams would be needed at the end of the hatchery stage and 277–645M clams would be needed at the end of the nursery stage to produce 1M bushels of fishable (120 mm) surfclams (Figure 2b; Table 1). Mean estimates of hatchery costs associated with this level of output ranged from $2.88 to $13.25M, nursery costs ranged from $0.81 to $1.88M and total costs ranged from $3.68 to $15.13M

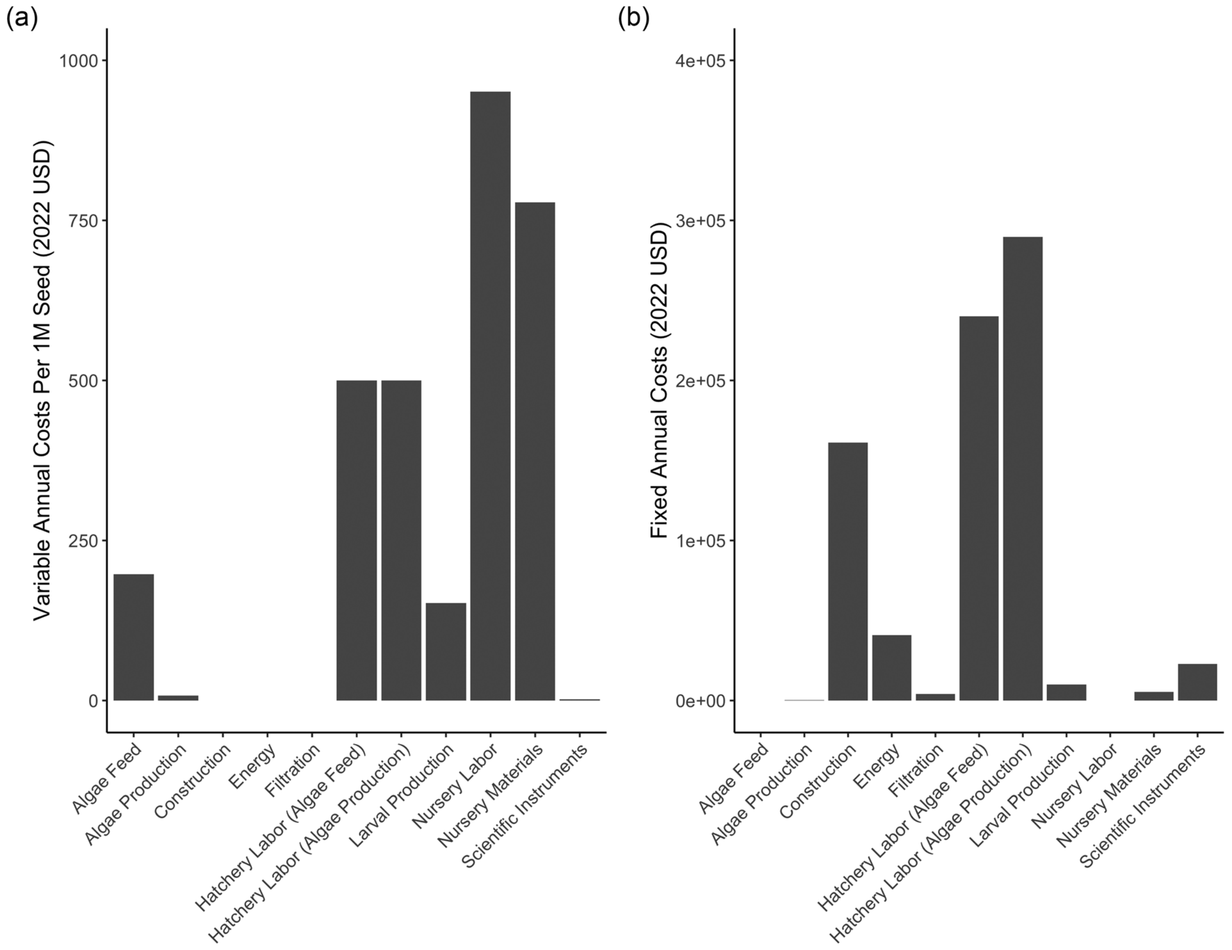

FIGURE 3 Estimated cost range (in 2022 USD) per cost category for variable annual costs per M surfclams (a) and for fixed annual costs (b).

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 and nursery) and in natural setting.

	Larval			Hatchery		Nursery		Ocean	
	Per cent survival (%)	Initial population	Final population	Per cent survival (%)	Final population	Per cent survival (%)	Final population	Per cent survival (%)	Final population
Maximum survival	60	940,000,000	564,000,000	66	373,932,000	74	276,709,680	Year 1: 78	217,770,518
								Year 2: 79	172,909,791
								Year 3: 80	138,327,833
								Year 4: 80	110,662,267
								Year 5: 80	88,529,813
Average survival	43	4300,000,000	1849,000,000	44	809,862,000	48	387,114,036	Year 1: 70	269,431,369
								Year 2: 73	196,684,899
								Year 3: 77	150,660,633
								Year 4: 77	115,406,045
								Year 5: 77	88,401,030
Minimum survival	26	40,000,000,000	10,400,000,000	20	2080,000,000	31	644,800,000	Year 1: 57	367,536,000
								Year 2: 65	237,060,720
								Year 3: 72	170,683,718
								Year 4: 72	122,892,277
								Year 5: 72	88,482,440

TABLE 2 Estimated cost range (in M of USD) of the hatchery and nursery stages for three survival scenarios (maximum, average and minimum) to produce one million (1M) bushels of market-sized (>120 mm) surfclams.

	Hatchery		Nursery		Total	
	Cost (M)	Std (M)	Cost (M)	Std (M)	Cost (M)	Std (M)
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

Note: Standard deviation (std) in cost for each stage is provided.

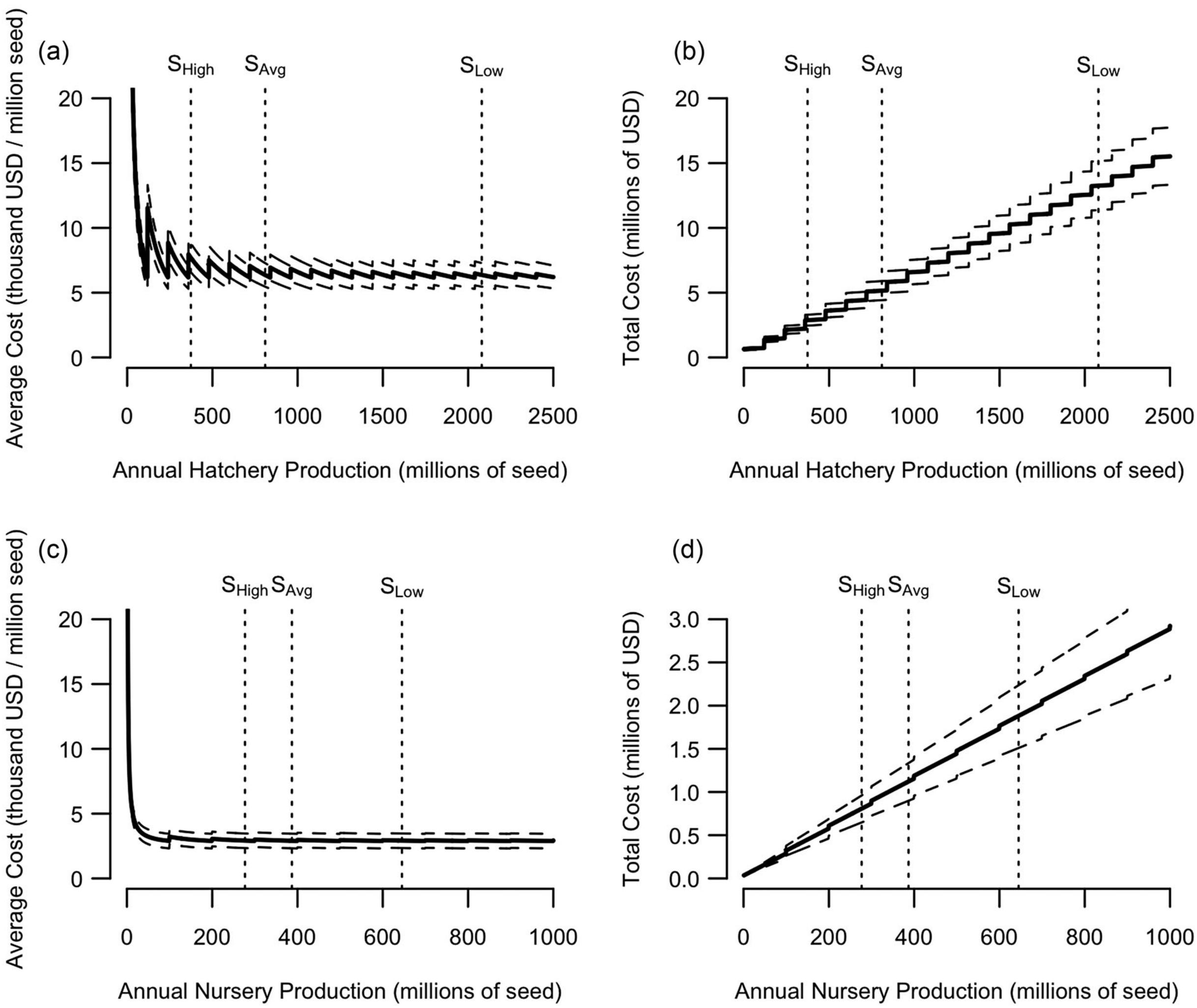

FIGURE 4 Average and total costs (in 2022 USD) for annual hatchery (a and b) and nursery production (c and d). Panels A and C depict the average costs per one million (1M) seed.

(Table 2). These ranges represent production from 4 to 18 hatcheries and 3 to 7 nurseries. Uncertainty in total cost estimates increased at higher production levels as the number of required hatcheries and nurseries also increased (Figure 4). Coefficients of variation associated with mean cost estimates were modest: ~8% at the hatchery stage, ~10% at the nursery stage and ~6% for total costs; suggesting variability in input factor costs was not a substantial driver of cost variability overall. Clam survival, meanwhile, drove greater than fourfold differences in hatchery and total costs and a more than twofold difference in nursery costs. Average costs were between $6000 and $7000 per 1M clams produced at the hatchery stage and approximately $3000 per 1M clams produced at the nursery stage. Total and average production costs were ~7% lower for hatchery production using bottled microalgae.

4 | DISCUSSION

Recent landings in the commercial Atlantic surfclam fishery have averaged around 2M bushels per year (Northeast Fisheries Science Center (NEFSC), 2022). Here, we estimate the annual effort necessary to produce enough seed to result in 1M bushels available to the fishery per year, or ~50% contemporary landings. At that scale, the costs of hatchery production may be less than the ex-vessel revenues generated by landed product, which regularly sells for \$14–\$17/bushel. Several questions remain surrounding ocean harvesting, land acquisition, permit availability and whether stock enhancement of the Atlantic surfclam could be a profitable venture. If, however, stock enhancement was to be used as a compensation strategy for damages imposed by offshore wind energy development, it is possible that such a programme could be unprofitable yet still welfare enhancing (i.e. if the negative profits of stock enhancement are smaller than losses arising due to offshore wind energy development). Close to 10% of all commercial surfclam landings, valued at over \$2M, came from offshore wind lease areas between 2015 and 2019 (NOAA, 2021), and a recent study estimated revenue losses ranging from 3% to 15% for the sector due to displacement from fishing grounds by offshore wind energy (Munroe et al., 2022; Scheld et al., 2022). This suggests that an enhancement programme could operate unprofitably yet still improve outcomes overall.

Large-scale hatchery production to support both conservation and commercial objectives has become widespread across marine species and locations. In the United States, hatchery-reared marine and anadromous finfish, crustaceans and molluscs are released into the wild for stock enhancement purposes (Kitada, 2018). Currently, Pacific salmon hatchery releases represent one of the largest fishery stocking programmes in the world. In 2021, the commercial salmon fleet in Alaska caught over \$140M of hatchery-raised salmon, which accounted for 28% of total statewide salmon harvests (Wilson, 2022). The Japanese scallop fishery in Hokkaido is managed through mass-release of cultured juveniles, removal of predators and rotational fishing efforts (releasing 1-year old juveniles and harvesting the animals 3 years later) to improve catch consistency after the initial fishery collapsed in 1945 due to overharvesting (Uki, 2006). These enhancement strategies have resulted in current harvests of ~300,000 tonnes per annum, compared to previous harvests of 100 tonnes per annum after the stock crash (Uki, 2006). Similarly, aquaculture and sea-ranching programmes in the Bay of Brest in France has provided 55% of the total Bay scallop landings between 1999 and 2004, thus greatly improving the decimated scallop fishery and enhancing economic sustainability in the region (Alban & Boncoeur, 2008).

Despite the wide use of hatchery-supported stock enhancement by national, state and local governments, ocean ranching has not commonly found private commercial success due to low recovery rates, capital intensity, market conditions and resource access rights (Arnason, 2001). Although many stock enhancement programmes have been found to be economically unsustainable (Arnason, 2001; Hilborn, 1998; Kitada, 2018), examples of net beneficial stock enhancement programmes do exist (e.g. Sproul & Tominaga, 1992), and the economic impacts of hatchery-supported production can be substantial. Whether stock enhancement is beneficial or not is still an open question in the world of seafood production. More studies are needed to assess the viability of large-scale enhancement efforts to compare costs and benefits and the expected returns regarding survival rates to determine the efficacy of enhancement. This research provides a robust analysis of the primary factors determining the viability of costs for hatchery and nursery production and the survival rates of Atlantic surfclam. However, this study could not be used to determine the viability of large-scale enhancement for other marine species or Atlantic surfclam in a different geographic location. This is due to context-specific differences within varying species and locations, such as survival rates, and limited details on costs and benefits associated with enhancement, such as variable nursery and hatchery costs. Therefore, this research could be extended to look further into other fishing sectors, marine species and geographical locations. Shellfish aquaculture can provide a variety of ecosystem services, such as habitat provisioning (Shinn et al., 2021; Theuerkauf et al., 2021), water filtration (Barr et al., In Press; Zu Ermgassen et al., 2012), nutrient cycling (Humphries et al., 2016; Kellogg et al., 2013; Lunstrum et al., 2018) and sediment stabilization (Donaldi et al., 2013). Advances in the ability to quantify and value these services may increase opportunities associated with green financing and investment (O'Shea et al., 2019).

Across all shellfish species produced regionally (oysters, clams and scallops), there are 28 commercial or municipal shellfish hatchery and nurseries and 4 focused on research in the Mid-Atlantic (New York to Virginia). Expanding this region to include New England, there are 37 commercial or municipal and 7 research hatcheries and nurseries (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.

Several important caveats must be acknowledged when considering the results of this study. First, 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 reliably estimated. In addition, transportation costs between hatchery and nursery facilities were not reported. These costs were assumed to be minimal as shellfish hatcheries in the region are frequently located proximally to nurseries. Second, the costs of planting seed in the ocean were not included because the planting locations and methods for planting have not yet been determined, and variations could result in substantially different costs. Likewise, the costs and efficiencies associated with collecting (fishing for) market-size surfclams following grow out were 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. Additionally, any incidental mortality incurred during the collection of the clams was not applied in our calculation, and depending on the collection method, this might result in losses that warrant review. Co-production of multiple bivalve species was not considered but is common in shellfish hatcheries. If co-production was included here, it should be expected to increase costs, reduce surfclam output or, likely, both. These limitations are potential areas for future research. The results presented here should therefore be regarded as a lower bound of the true costs of hatchery-supported stock enhancement for Atlantic surfclam.

Another important consideration that was not directly addressed in this study was the availability of suitable locations to accommodate the necessary hatcheries, nurseries and grow out to market size, which is a critical area for future research. Hatchery and nursery facilities are typically located in areas adjacent to or near 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 Mid-Atlantic coastal states, waterfront property tends to be highly sought after and the availability of lands adjacent to waters of the appropriate standards (salinity, temperature and sanitation) may be an impediment. The availability and suitability of locations for outplanting seed clams were also not considered. Given the vast areas over which the commercial fishery operates, there is a great deal of Atlantic surfclam habitat along the Mid-Atlantic 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 were not accounted for in this study and are areas for future research.

Finally, in estimating maximum and minimum survival in hatchery, nursery and ocean conditions, reports of zero survival were excluded. The literature often fails to report circumstances of hatchery and nursery failures (Gray et al., 2022), and it is not well known how frequently such events may occur. Increasing the number of hatcheries and nurseries used in production could reduce the risk of total failure across locations, though this would come with increased costs. As our estimates include a minimum, non-zero, survival assumption each year as a worst case scenario, survival may be overestimated and thus costs underestimated. However, although hatchery and nursery costs substantially increase across the survival scenarios, cost variability within a particular survival scenario is relatively less impactful. This indicates that economic viability depends considerably on survival rates at different production stages. Additional research is needed to better understand the drivers of hatchery and nursery failures and how large-scale shellfish aquaculture production can hedge against these risks. Furthermore, although this research provides insight into the viability of fishery-scale enhancement efforts for Atlantic surfclam, this research is an important step towards estimating how enhancement efforts can be accomplished at a large-scale with impactful results. Similar approaches to this research may be considered in other contexts for various fishing sectors to expand future research where enhancement efforts may be beneficial for economic or conservation targets.

AUTHOR CONTRIBUTIONS

Caela Gilsinan and Sarah Borsetti: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; visualization; writing—original draft; writing—review and editing. **Daphne Munroe**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **Andrew Scheld**: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest in this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

This work did not require ethics approval.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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