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A Bioeconomic Analysis of Sea Scallop (Placopecten Magellanicus) Aquaculture in the Gulf of Maine

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A BIOECONOMIC ANALYSIS OF SEA SCALLOP (PLACOPECTEN MAGELLANICUS) AQUACULTURE IN THE GULF OF MAINE

By

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An Abstract of the Thesis Presented
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Aquaculture is the fastest growing food production sector in the world. In the Northwest Atlantic, interest in Sea Scallop (*Placopecten magellanicus*) (hereafter scallop) aquaculture has grown rapidly in the last decade. In the U.S., scallops support a ~$1 billion USD industry with nearly $500 million coming from imports. By comparison, the U.S. exports only ~$139 million USD of scallops annually. This substantial trade imbalance and strong domestic demand has created an opportunity for a farmed product to capture a share of the market. However, technical, regulatory, and, perhaps most importantly, economic challenges have stifled the growth of scallop aquaculture in the Northwest Atlantic. We performed semi-structured interviews (n = 7) with the majority of scallop farmers in Maine, USA to parameterize a scallop aquaculture bioeconomic model. To identify production bottlenecks and assess the influence of various biological and market variables on farm-scale success, we conducted financial simulations for farms of various sizes targeting either live "whole" scallops or the traditionally consumed shucked adductor muscle "meat".

The end product (“whole” or “meat”) had a large influence on the profitability of farms. For example, farms selling > 200,000 whole scallops year^{-1} were profitable. However, all farms selling shucked meats generated negative returns. Labor made up the greatest portion of costs in all model simulations and increased linearly with farm size, representing a significant bottleneck. Farm value was most sensitive to changes in market price, time to market, and annual sales. Businesses selling whole scallops can potentially be successful, but regulatory or labor mechanization issues could hinder further expansion of the industry. Our analysis suggests four strategies to increase farmed scallop production in the Northwest Atlantic: (1) develop methods to mechanize low density net culture, (2) optimize net stocking densities, (3) build site selection tools that decrease time to market, and (4) invest in end-markets and biotoxin testing for whole scallops. Diversifying the shellfish aquaculture sector by increasing the viability of scallop aquaculture has the potential to play a key role in increasing the economic resilience of coastal communities.

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I'd like to thank my committee, Damian Brady, Dana Morse, and Joshua Stoll, for providing guidance, expertise, and comments throughout the duration of this work. I'm also grateful to Christian Brayden of the Maine Aquaculture Association for providing comments and guidance on the interview script and the bioeconomic model. He was incredibly generous with his time.

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NPV - Net present value

COP - Cost of production

CHAPTER 1

INTRODUCTION

1.1 Background and rationale

Despite boasting the world's largest Exclusive Economic Zone (EEZ), the United States is the global leader in seafood imports (FAO, 2020). The U.S. is home to well managed and lucrative wild fisheries that generate substantial economic value (National Marine Fisheries Service, 2020) and support ~1.7 million jobs (National Marine Fisheries Service, 2018). Yet over 70% of the seafood consumed domestically, including the ~20% made up by reimports (Gephart et al., 2019), is imported. Approximately 60% of this volume is farmed (National Marine Fisheries Service, 2020). Aquaculture is the fastest growing food production sector in the world (FAO, 2020) and has been heralded as a means to sustainably increase domestic production of fish and shellfish without further exacerbating wild stocks (Gunning et al., 2016; Lester et al., 2018). For example, the U.S. wild Atlantic Sea Scallop (*Placopecten magellanicus*) (hereafter scallop) fishery is the nation's fourth most valuable species (National Marine Fisheries Service, 2020). Demand for scallops far outstrips supply and the U.S. imports an almost equal value of various farmed scallop products from Asia and South America (Hale Group, Ltd, 2016; OECD, 2020). In total, the scallop market is a nearly $1 billion USD industry in the United States (FAO, 2020) and the existence of a substantial trade imbalance represents significant opportunities for a domestically farmed product to capture a portion of this share.

Efforts to establish a scallop aquaculture industry in the Northwest Atlantic (i.e., the U.S. and Canada) began in the 1970's, but in the last four decades development has been stifled by technical barriers. Employing techniques mainly borrowed from Japan, growers and researchers have explored the feasibility of wild spat collection (Cyr et al., 2007; Morse, 2015), suspended lantern net culture (Coleman et al., 2021; Grecian et al., 2000; Parsons & Dadswell, 1992), and "ear-hanging" (Dadswell & Bradford, 1991; Grant et al., 2003). These trials demonstrated baseline feasibility of the techniques from a biological standpoint, but there are still significant economic barriers to the industry (Claereboudt et al., 1994; Penney & Mills, 2000; S. E. Shumway & Parsons, 2016).

Low density net stocking, slow growth, biofouling, and biotoxins are the primary inhibitors of profitability. Scallops are particularly sensitive to stocking density, and overstocking can decrease growth and lead to product loss (Coleman et al., 2021; Parsons & Dadswell, 1992; Penney, 1996). The demands of low density net stocking, and prolonged (3+ year) time to market, generate high labor and equipment costs for growers (Parsons & Dadswell, 1994). In an analysis of sea scallop aquaculture in Newfoundland, Penney and Mills (2000) observed that labor made up ~30% of annual costs for farms selling 500,000 - 1,000,000 scallops year^{-1} (Penney & Mills, 2000). Gilbert and Cantin (1987) conducted a similar financial analysis and noted that consistently increasing lines of credit to fund nets and mooring systems proved insurmountable for growers (Gilbert & Cantin, 1987). While Gilbert and Cantin (1987) concluded that selling the traditionally consumed shucked adductor "meat" alone would generate negative returns, Penney and Mills (2000) observed that farms selling whole live scallops could be profitable. Shucked meats comprise the vast majority of scallop products consumed in North America. The meat, however, only makes up ~10% of the mass of each landed scallop (National Marine Fisheries Service, 2020). Bringing whole scallops to market significantly increases the yield from each individual, but poses considerable challenges for growers. Frequent, and often costly, testing for the presence of the biotoxins Amnesic Shellfish Poisoning (ASP) and Paralytic Shellfish Poisoning (PSP) within the viscera and roe is required (Shumway et al., 1988). The combined effects of these hurdles have limited the industry to a handful of operational farms in the U.S. and Canada. Currently, farmed scallops represent <1% of annual scallop sales in North America (Shumway & Parsons, 2016).

1.2 Research Questions

In the last decade, close collaboration between researchers, governmental agencies, and growers in the United States has led to technical and regulatory breakthroughs and a renewed interest in scallop aquaculture (Maine Department of Marine Resources, 2017; Morse, 2017). Delegations of Maine fishermen, farmers, and extension agents have traveled to Japan and returned with expertise and equipment specifically designed to manage biofouling and increase scallop growth, leading to potential reductions in labor costs (Beal et al., 1999; Coastal Enterprises, Inc., 2019). Similarly, an agreement between growers and the state agency charged with regulating shellfish with respect to public health, the Maine Department of Marine Resources (DMR), has resulted in a biotoxin testing policy that allows for the sale of whole live scallops (Maine Department of Marine Resources, 2017). As a result of these successes, the first U.S. sales of live farmed scallops were completed in 2019 (Dana Morse, *pers comm*). Despite the early success of a handful of farms, considerable questions remain about the economic viability of suspended net culture, the value of whole scallops in a competitive U.S. seafood market, the ability of growers to profitability target "meats" alone, and the effect of various biological, technical, and market variables on farm level success (Coastal Enterprises, Inc., 2019).

Bioeconomic models are a useful tool for untangling the complex human-ecosystem relationships that often dictate the profitability of aquaculture operations (Choi et al., 2006; Fuentes-Santos et al., 2017). We conducted semi-structured interviews with growers in Maine to inform a bioeconomic model. Our primary goal was to analyze the feasibility of, and potential bottlenecks to, the emerging scallop aquaculture industry. We compared the success of farms operating at various production scales and targeting different end products (whole scallops vs. meats) under a variety of market and production scenarios. Scallops appear to be a prime candidate to expand and diversify the rapidly growing bivalve aquaculture sector in the Northwest Atlantic. The results of this work will help growers make informed husbandry and business decisions and identify future research priorities.

CHAPTER 2

METHODS

2.1 Semi-structured interviews

We conducted semi-structured interviews (n = 7) with the majority of scallop farmers in Maine, USA. Interviews lasted between 1 and 2 hours and were carried out with two primary goals: (1) to collect quantitative production data to accurately parameterize a bioeconomic scallop aquaculture model and (2) to catalog the most pressing Research & Development (R&D) challenges facing this nascent industry in the Northwest Atlantic. For example, to collect data relevant to goal (1) growers were asked to describe their production process as well as all fixed and operating costs relevant to the business. Labor expenses were calculated from the time required to complete production tasks and the quantity of scallops brought to market annually. The more qualitative R&D cataloging within goal (2) was used to select relevant parameters for sensitivity analyses conducted with the bioeconomic model and inform future research priorities. The interview script is available in Appendix A.

Decisions about which farmers to interview ran as follows. Currently, there are 167 active standard aquaculture leases and 676 active limited purpose aquaculture licenses (LPA) in Maine (DMR, 2021). Of these 843 leases and licenses, 193 list scallops as an approved species (DMR, 2021). The vast majority of these scallop growers are primarily focused on other species (i.e., oysters, mussels, or kelp), experimenting, or not growing scallops at any scale. We therefore chose participants that were operating at a commercial scale (at least 2 years of experience or actively selling scallop products) for interviews. The average number of years growing scallops ranged from 2 to 8 among participants (mean = 4 years). Growers were distributed between southern Maine and the "Downeast" region, with farms located in both the warmer Western Maine Coastal Current and the colder Eastern Maine Coastal Current (Pettigrew et al., 2005). One farmer we spoke with was not actively growing scallops, but had dedicated a considerable amount of time to the industry and had only recently transitioned to a different species.

2.2 Production model parameter selection

Based on the semi-structured interviews with industry leaders, we built a scallop aquaculture bioeconomic model to examine four distinct production scenarios: (1) a business targeting a whole 75 mm scallop with all costs included, (2) the same business in scenario (1) but with the cost of the boat and work truck removed (representative of fishermen who have transitioned to scallop aquaculture and already own equipment), (3) a business exclusively targeting the traditionally consumed shucked adductor "meat", and (4) the same business as scenario (3) with the cost of the boat and truck removed. For scenarios 2 and 4, we also assume that the upfront costs of two pieces of specialized equipment, a scallop washer and grader, are distributed evenly between nine other growers. This cooperative model of equipment sharing has been demonstrated successfully in Maine by interview participants.

The schedule of each scenario closely follows the practices described by the growers. Production tasks can be divided into three distinct stages: spat collection, juvenile culture, and final grow-out. Spat collectors are deployed in the fall, checked monthly over the course of the winter, and then retrieved the following spring. Spat is then sorted and stocked into lantern nets, indicating the start of juvenile culture. Stocking densities are then reduced in the fall for overwintering and bio-fouled nets are swapped out for clean nets. At the start of the grow-out stage the following spring, scallops are washed, size graded, and stocking densities reduced a second time. For production scenarios 1 and 2 (whole scallops), first harvest is carried out during the fall of the third year when scallops reach 75 mm (19 months post initial stocking into 6 mm mesh lantern nets). However, for scenarios 3 and 4 ("meats" only), an additional reduction in stocking densities in the fall followed by another full year of grow-out is required due to the size demands of the adductor market. For these farms, the first harvest is carried out in the summer of the following year, 30 months post initial stocking into 6 mm mesh lantern nets, when scallops are > 110 mm. At this size, 15 - 20 scallop meats will make up a pound, commonly referred to as a '15 - 20 count' meat. The 'count' system is used in the Northwest Atlantic wild scallop fishery as a means of size grading.

The growth rates, time to market projections, and mortality rates used in all scenarios are dependent upon low density net stocking. Based on conversations with growers, we used a stocking schedule of 250 individuals $tier^{-1}$ in the first spring during juvenile culture (6 mm diameter mesh nets), 50 individuals $tier^{-1}$ in the first fall during juvenile culture (12 mm diameter mesh nets), and then ultimately 15 individuals $tier^{-1}$ in the second spring during grow-out (12 mm diameter mesh nets). For scenarios 3 and 4, there is an additional thinning down to 5 individuals $tier^{-1}$ in the fall of the second year during grow-out. Based on this stocking and handling schedule, growers relayed that an annual mortality rate of 12.5% can be expected. Therefore, we use this value for all scenarios.

There are a few major assumptions in the production model that impact our economic simulations for scenarios 1 and 2. The farmed scallop market in the U.S. is very small and the sale of in-shell products is predicated on testing for the presence of biotoxins (Maine Department of Marine Resources, 2017). While we account for the cost of regulatory biotoxin testing to satisfy public health requirements in Maine, USA, we also assume consistent year round sales in all four production scenarios (i.e., no closures). Closures or restrictions within scenarios 1 and 2 could significantly lower revenues and alter model outputs.

2.3 Economic model parameter selection

We constructed cash flow models with 10-year timelines that include all relevant fixed and operating expenses for each of the four production scenarios (Appendix B). Equipment costs were sourced directly from suppliers when not provided during interviews. The lifespan of depreciable capital items was informed by the relevant experience of growers. We then used a straight-line depreciation schedule with no salvage value to calculate depreciation costs. All scenarios assume the use of 244 m (800 ft.) longlines spaced 30 m (100 ft.) apart. All lease application fees and ongoing lease rent fees are included and unique to the state of Maine, USA. A 50:50 split between owner equity and debt was used to calculate the present value and repayment schedule for a ten-year term loan with a 7.5% coupon for depreciable assets.

Given the size of the farmed Sea Scallop market, < 1% of total annual U.S. Sea Scallop sales (Shumway & Parsons, 2016), ex-farm market prices will most likely be subject to future increases in supply and competition from the wild Bay and Sea Scallop fisheries. Therefore, we used a conservative price estimate of $1.00 for a whole 75 mm scallop, a value well below the historic sale prices relayed by growers. For scenarios 3 and 4, we used a market price of $10.50 lb.$^{-1}$ of shucked scallop meats provided by the Maine DMR for 2019 (ME DMR, 2020).

2.4 Bioeconomic model simulations

We primarily tracked two model outputs: cost of production (COP; $ scallop^{-1}) and net present value (NPV; $). COP is formulated as

$$COP = \sum_{t=1}^{n} \frac{CF_n}{S_n}$$

where t is the number of time periods, CF_n is the net cash flow during a single period n, and S_n is the quantity of scallops produced during a single period n. This analysis does not include a market price, and provides a generalizable evaluation of startup performance over a 5 (COP5) or 10 (COP10) year timeline. NPV is the discounted sum of all future cash flows over a period of time, and is a method commonly used, through discounting, to evaluate a project based on a next best alternative. NPV is calculated as

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1 + i)^t}$$

Where R_t is the net cash inflow minus outflows during a single period t, i is the interest rate used to discount future cash flows, and t is the number of time periods. We used a 7.5% discount rate to calculate NPV over 5 (NPV5) and 10 (NPV10) year timelines.

To quantify the effects of farm size on COP5, we iteratively increased annual sales by 10,000 scallops year^{-1} from 200,000 to 1,000,000 scallops year^{-1} and calculated a corresponding COP5 for each scenario. Within each of our four production scenarios, we then assumed farms of three different sizes: 200,000 (200K), 600,000 (600K), and 1,000,000 scallops year^{-1} (1M). For each farm, we projected cash flows and calculated corresponding COP and NPV over 5 and 10 year time periods. We then cataloged the cost structure of the 200K, 600K, and 1M farms in scenarios 1 and 3. We also calculated the market price needed to "break-even" (NPV5 > 0) for each of the three farm sizes (200K, 600K, 1M) in each scenario.

We performed sensitivity analyses on the 600K farms in scenarios 1 and 3 (costs of boat and truck included) only. We first analyzed the effects of changing key labor input parameters on COP5. In +/- 5% increments, we iteratively changed the time required to complete three tasks: 1) sort seed, 2) reduce stocking densities and clean nets in the fall of juvenile culture, and 3) reduce stocking densities while washing and grading scallops in the spring of grow-out. We then calculated a corresponding COP5 under each condition. For the 600K farm in scenario 3, we included a 4th task, the time required to reduce stocking densities and clean nets for overwintering in the fall of grow-out, in our analysis. We then tracked the effects of iteratively changing, in +/- 5% increments, farm size, mortality rate, spat collection success, labor inputs, market price, and scallop growth rate on NPV5.

2.5 Stochastic Monte Carlo analysis

Finally, we performed a *Monte Carlo* analysis to assess risk as a function of potentially random key variables (Chen et al., 2017; Valderrama et al., 2016). We ran 500 iterations of four separate simulations using the 600K farm in scenario 1. We assumed that market price, annual mortality rate, spat collection success, and a combination of the three variables were triangularly distributed random variables. For each analysis we assumed a best, worst, and most likely value for each parameter. Market price was bound between $0.70 - $1.30 with a most likely value of $1.00, annual mortality was bound between 2.5 - 24.5% with a most likely value of 12.5%, and spat collection success was bound between 300 - 2,700 spat collector^{-1}, with a most likely value of 1,500 spat collector^{-1}. Best and worst case scenarios represent the range of values provided by interview participants for mortality and spat collection. However, the range of market prices is based on a reasonable estimation of the upper and lower bounds for a commercial operation.

CHAPTER 3

RESULTS

3.1 R&D priority cataloging

During the semi-structured interviews, growers consistently referenced seven main themes: site selection, spat supply, biofouling, optimization and mechanization, biotoxins, end market uncertainty, and scale. Notably, there was an even distribution of references to each theme across all of our interviews (Figure 1). These data were used as the basis for selecting farm size, mortality rate, spat collection success, labor inputs, market price, and scallop growth rate as relevant sensitivity analysis parameters.

3.2 Production scenario results

We observed clear economies of scale for farms in all four scenarios. Annual sales were inversely proportional to COP5 (Figure 2). As we forced the model from 200,000 to 600,000 scallops year^{-1} in scenario 1, COP5 fell from $1.12 to $0.68 (Figure 2). However, as we continued to increase sales from 600,000 to 1,000,000 scallops year^{-1}, COP5 only fell from $0.68 to $0.59. Production costs ($ scallop^{-1}) were substantially higher for farms targeting shucked scallop meats (ranging from $1.73 - $2.77) than those for farms targeting whole scallops (Figure 2). Removing the cost of the boat and truck led to comparatively lower COP5 values for both the whole scallop and shucked meats ventures.

There were notable differences between the performance of farms targeting whole scallops and those bringing shucked meats to market. For whole scallop farms, an initial capital outlay was followed by two years of net negative cash flows before positive returns were realized in year three (Figure 3a). However, for farms in scenarios 3 and 4 (shucked meats), cash flows were negative over the entire 10-year model timeline (Figure 3b). The upfront costs for shucked meats farms were significantly higher than those for whole scallop ventures, driven by the lantern net and longline demands of low density (5 individuals tier^{-1}) stocking. For example, the initial outlay for a 600K whole scallop farm, in which the cost of the boat and work truck are included, totals $209,902 (Figure 3a). A comparable farm targeting shucked meats would require an initial investment of $411,921 (Figure 3b). All farms in scenarios 3 and 4 generated negative NPV5 and NPV10 (Table 1).

Labor made up the greatest portion of total costs for all farms in scenarios 1 and 3 (Figure 4). For the 200K farm in scenario 1, labor made up 40% of total costs. However, as farm size increased to 1M, labor costs increased to 61% of the total share (Figure 4a). Equipment depreciation costs were consistently higher in scenario 3 (meats) than in scenario 1 (whole scallops). A detailed look at the cost subcategories for the 600K farms in both scenarios 1 and 3 underscored the impacts of low density net stocking. Lantern nets accounted for 42.2% and 55.8% of depreciation costs, while stocking density reductions and net cleanings accounted for 75.4% and 87.6% of labor expenses, for the 600K farms in scenarios 1 and 3, respectively. Regulatory testing for the sale of whole scallops accounted for just over 4% of costs for a 600K farm in scenario 1. This value does not include any associated transportation expenses (fuel, time, etc.) to a certified testing center as the value would be too difficult to generalize between farms.

Additional benefits of scale were identified by tracking the effects of market price on NPV5. All farms in scenarios 1 and 2 "broke-even" (NPV5 > 0) with whole scallop market prices between $0.58 and $1.29 (Figure 5a). Break-even was achieved first for the 1M scallops year^{-1} farm in scenario 2, indicating substantial benefits of a pre-owned boat and truck. Conversely, break-even was never achieved across the full range of market prices ($0.10 -

\$25.10 $lb.^{-1}$) for any of the farms in scenarios 3 and 4 (Figure 5b). Only at a sale price of \$43.75 $lb.^{-1}$ was NPV5 > 0 for a 600K farm in scenario 3.

3.3 Sensitivity analyses

Changing the time required to handle nets before grow-out, compared to seed sorting or handling nets during juvenile culture, led to the biggest change in COP5 for the 600K farms in both scenarios 1 and 3. For example, for a whole scallop farm, a 25% increase in the time required to reduce stocking densities in the spring of grow-out resulted in a \$0.05 increase in COP5 (Figure 6a). For the 600K meats only farm, a 25% increase in the time required to reduce stocking densities to 5 individuals $tier^{-1}$ for an additional year of grow-out resulted in a \$0.17 increase in COP5 (Figure 6b).

Whole scallop farm NPV5 was most sensitive to market price and growth rate (Figure 7a). A 25% increase in market price (\$1.00 - \$1.28) or the amount of time required for scallops to reach 75 mm (19 - 24 months) resulted in a ~\$300,000 increase and a ~\$200,000 decrease in NPV5, respectively (Figure 7a). Increases in farm size exerted the most influence on NPV5 for the 600K meats only farm, but the effects were strongly negative. A 25% increase in farm size generated a \$282,000 decrease in NPV5 for the 600K farm in scenario 3 (Figure 7b).

3.4 Monte Carlo risk assessment

We performed a *Monte Carlo* analysis only using the 600K farm in scenario 1. Random price, spat collection success, and a combination of all three parameters resulted in 2.8%, 3.8%, and 5.2% chances of negative returns, respectively (Figure 8). Notably, the "worst-case" spat collection condition (300 spat $collector^{-1}$) produced the lowest NPV5 (-\$310,045) compared to the other three scenarios, indicating that variable spat collection is a potential source of risk (Table 2). While the probability of generating negative returns was low (2.8%) in the random price simulations, whole scallop price fluctuations could hinder profitability particularly in the startup phase (< 5 years).

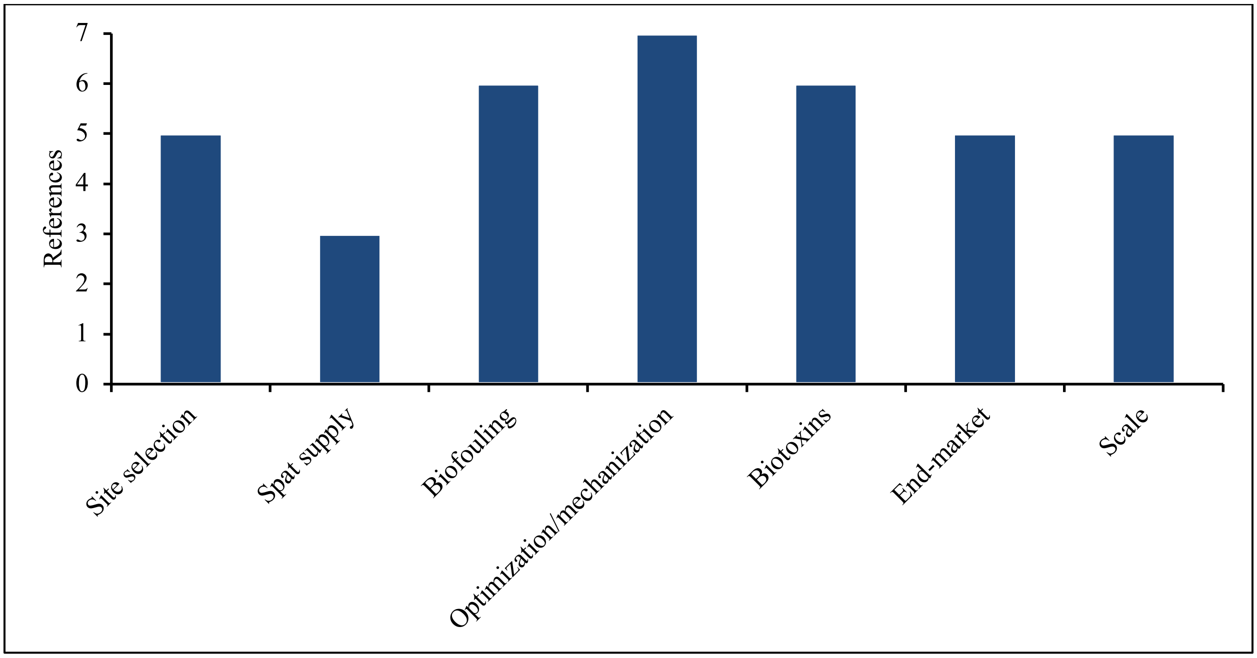


Figure 1. Number of references to emerging themes from semi-structured interviews (n=7) with scallop aquaculture industry leaders in the state of Maine. A reference indicates mention to a particular R&D challenge that falls under one of these 7 categories related to scallop production.

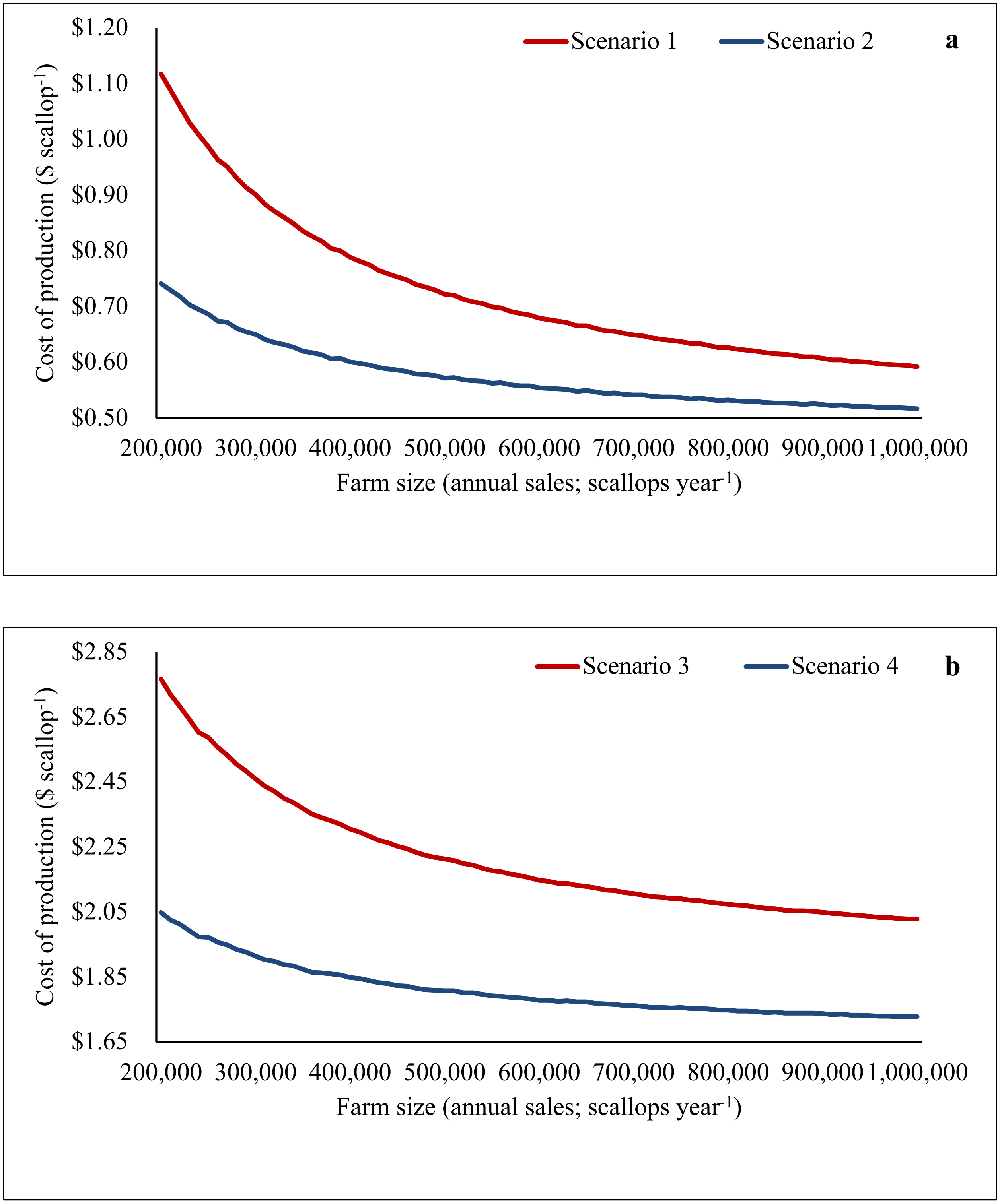


Figure 2. 5-year aggregated cost of production ($ scallop^{-1}) for scenarios 1 (a, red line), 2 (a, blue line), 3 (b, red line), and 4 (b, blue line) as a function of farm size (annual scallop sales).

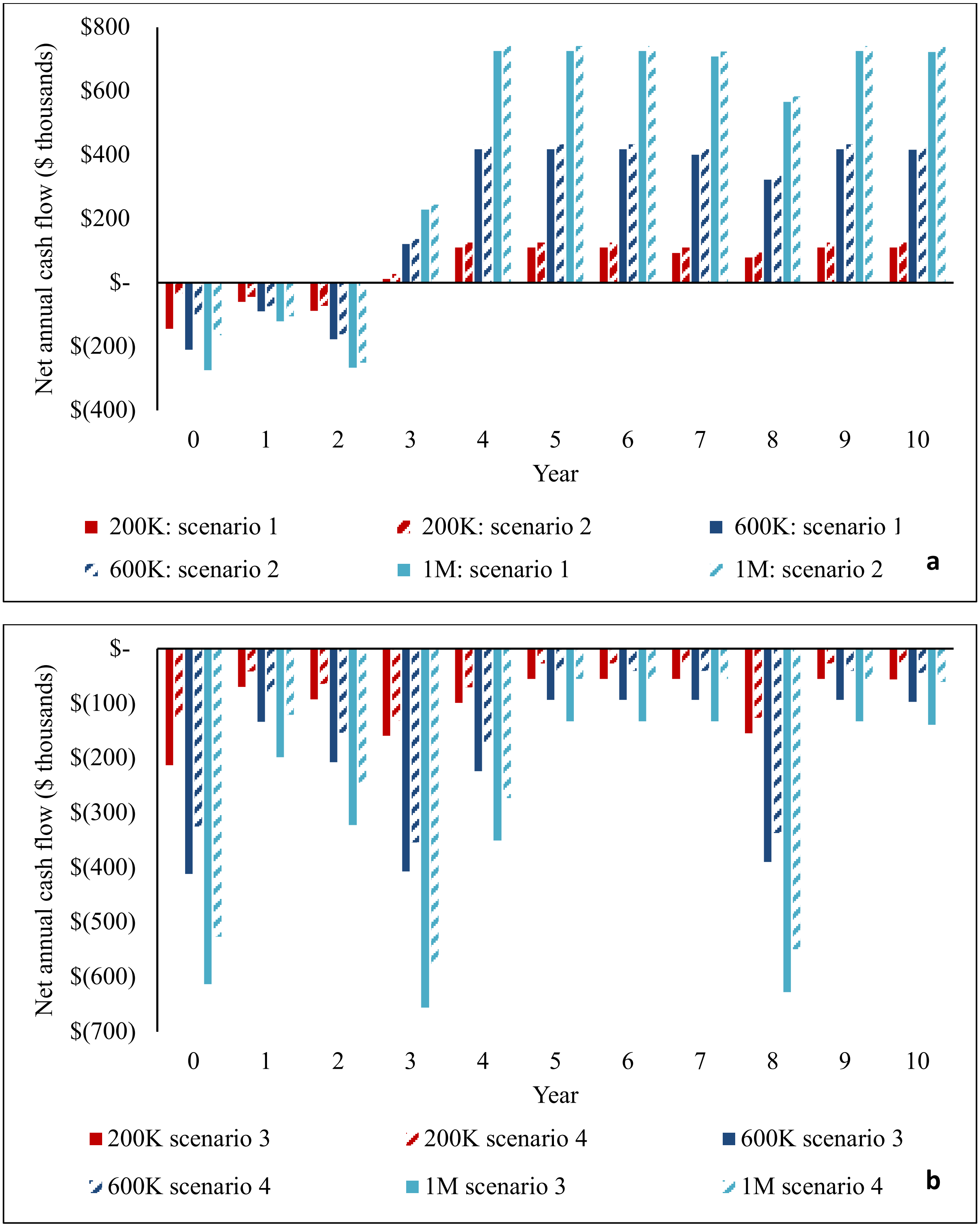


Figure 3. Net annual cashflows for farms of varying sizes in scenarios 1 (a, solid bars), 2 (a, striped bars), 3 (b, solid bars), and 4 (b, striped bars). Year 0 represents the initial capital outlay.

Table 1. Summary of NPV and COP results for 200K, 600K, and 1M farms in scenarios 1 – 4 over 5 and 10 year timelines. Negative NPV values are displayed in red.

Farm scenario	Farm size (annual sales)	NPV5	NPV10	COP5	COP10
***1:** Whole scallop, total investment*	200K	-$106,559	$177,473	$1.12	$0.70
	600K	$255,209	$1,369,913	$0.68	$0.45
	1M	$617,652	$2,562,985	$0.59	$0.40
***2:** Whole scallop, pre-owned boat and truck*	200K	$66,552	$395,264	$0.74	$0.53
	600K	$428,291	$1,587,703	$0.55	$0.39
	1M	$790,733	$2,780,775	$0.52	$0.37
***3:** Shucked meats, total investment*	200K	-$598,257	-$809,552	$2.77	$1.40
	600K	-$1,275,488	-$1,706,285	$2.15	$1.16
	1M	-$1,958,856	-$2,613,113	$2.03	$1.12
***4:** Shucked meats, pre-owned boat and truck*	200K	-$397,650	-$529,461	$2.05	$1.12
	600K	-$974,962	-$1,256,677	$1.78	$1.01
	1M	-$1,557,598	-$1,992,697	$1.73	0.98

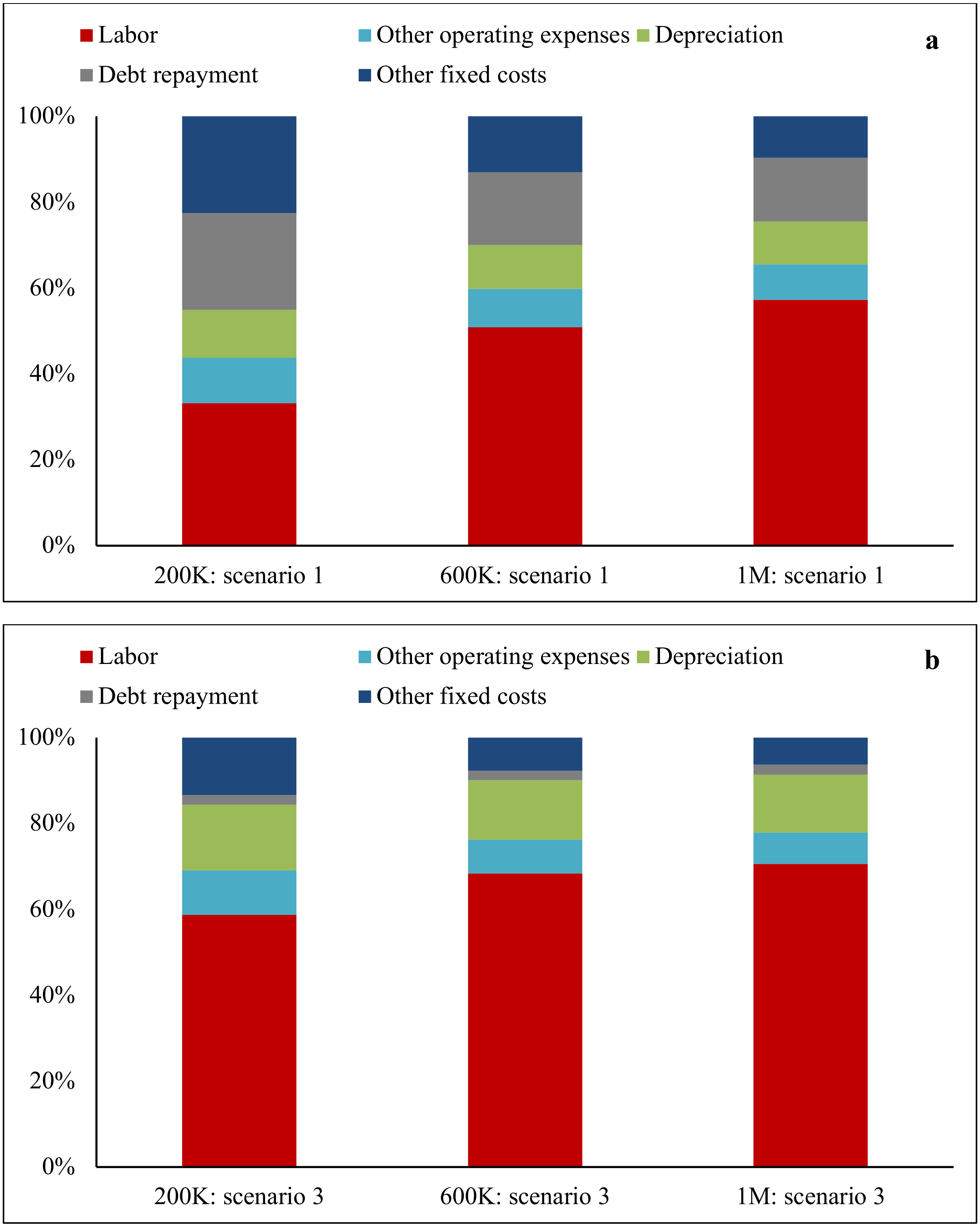


Figure 4. Cost breakdown for 200K, 600K, and 1M farms in scenarios 1 (a) and 3 (b).

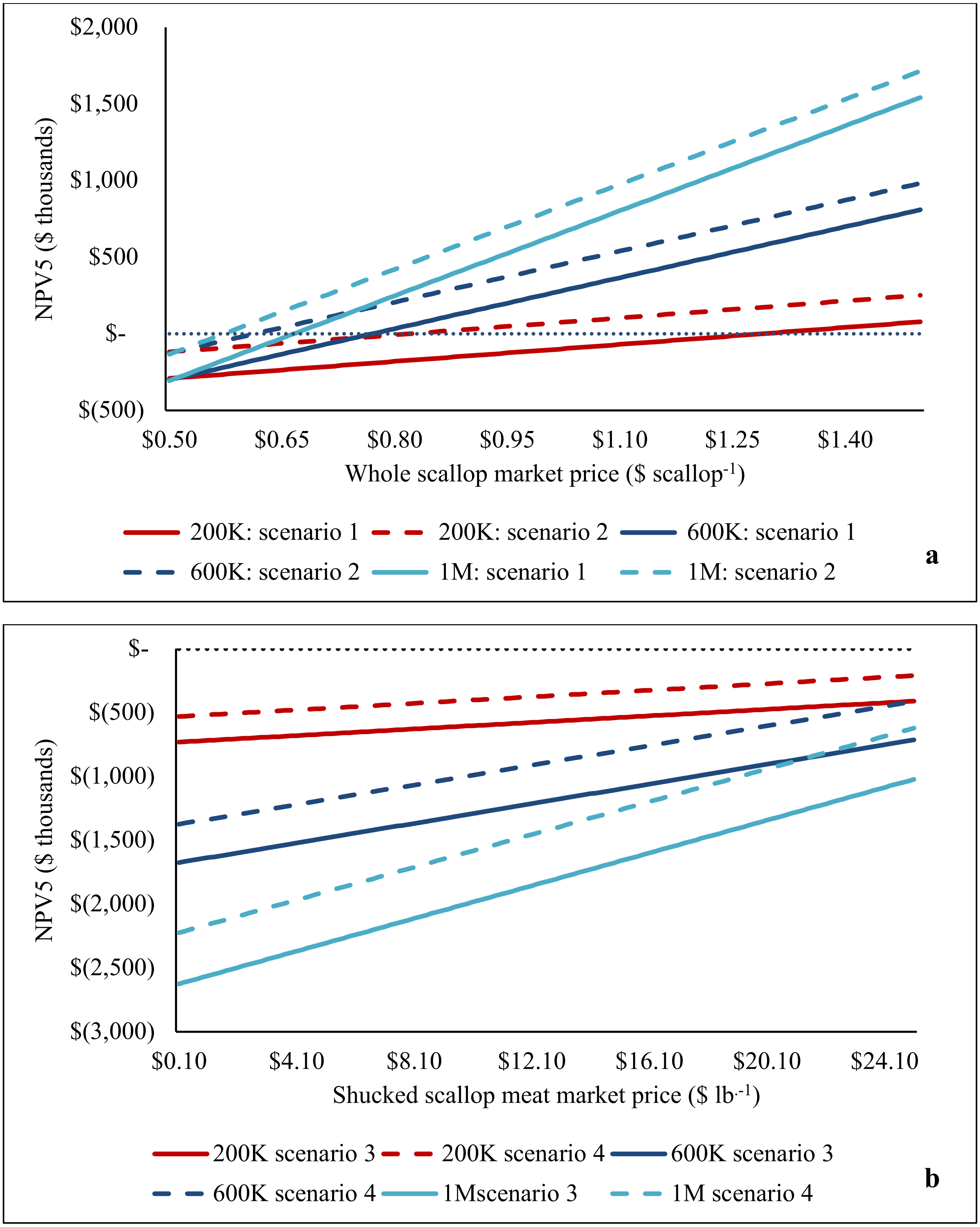
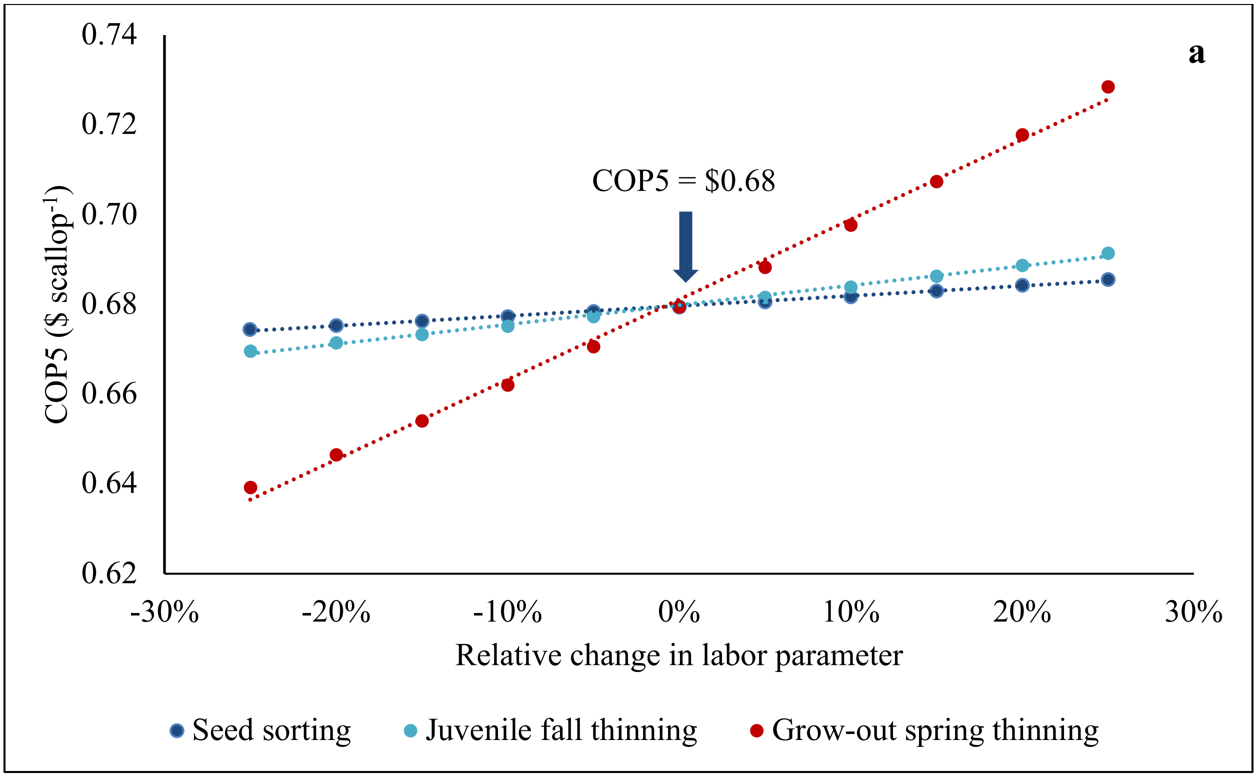


Figure 5. Net present value (NPV5) for farm of three different sizes in scenarios 1 (a), 2 (a), 3 (b), and 4 (b). The dashed horizontal line denotes NPV5=0.



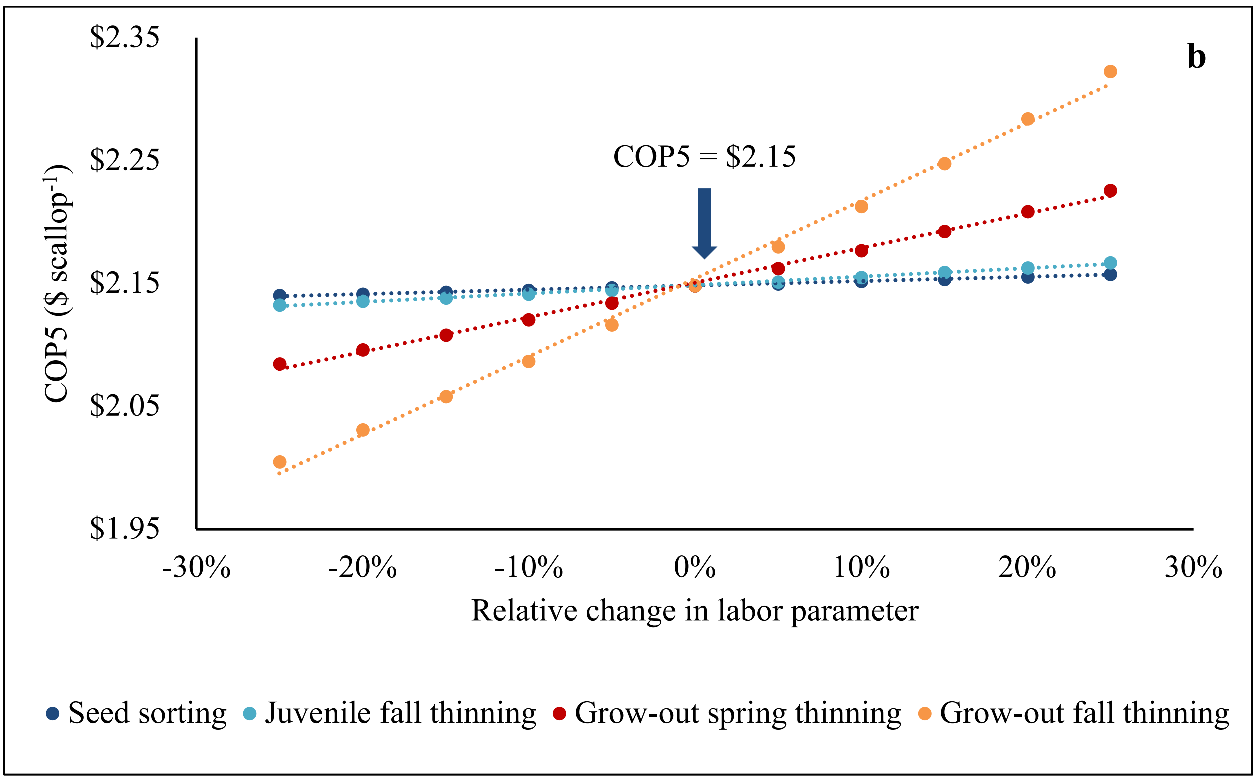


Figure 6. Effects of changes in key labor input parameters for a 600K scallops year^{-1} farm in scenarios 1 (a) and 3 (b) on cost of production ($ scallop^{-1}).

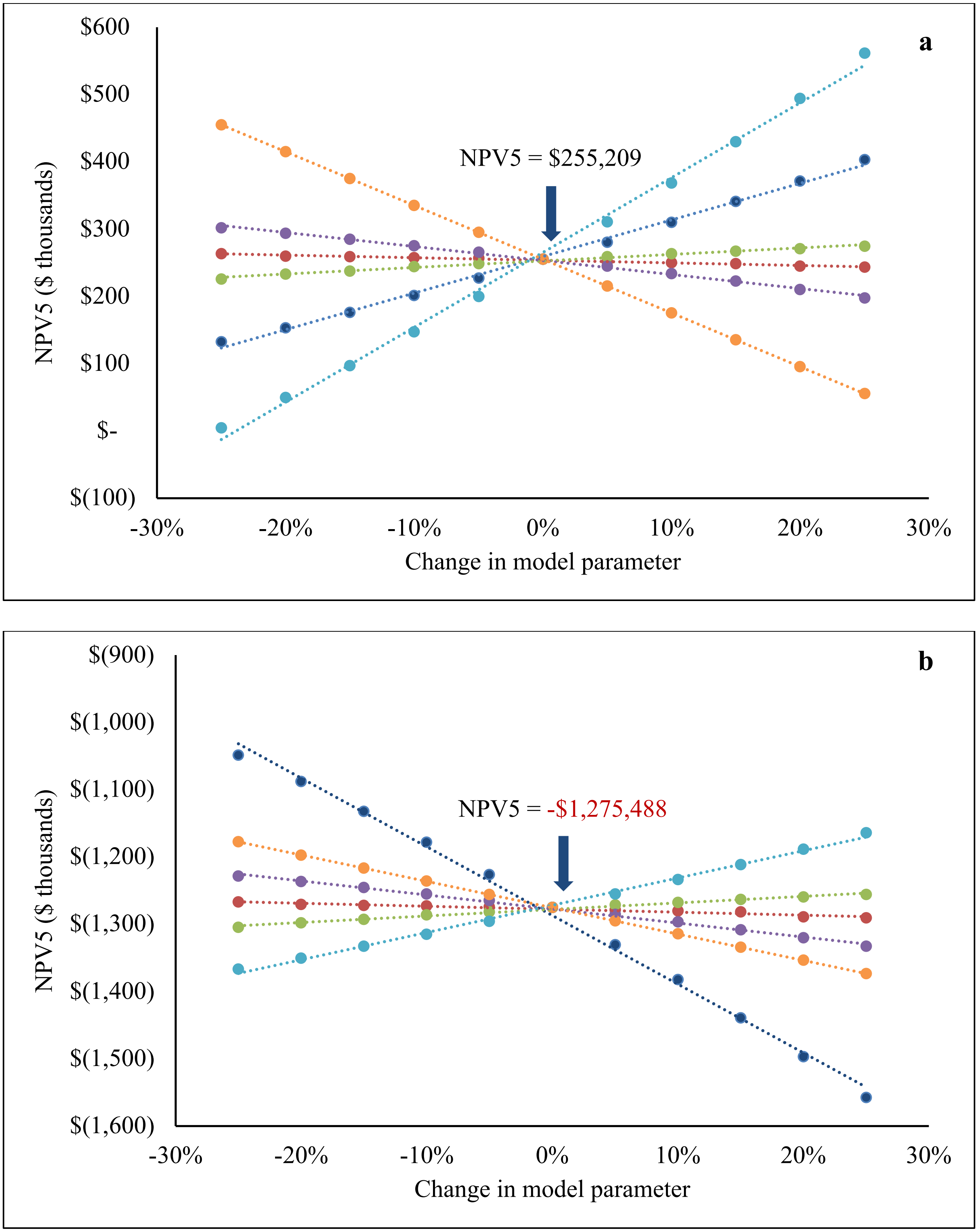


Figure 7. Effects of changes in key model parameters on NPV5 ($) for 600K scallops year^{-1} farms in scenarios 1 (a) and 3 (b).

Table 2. Summary of stochastic Monte Carlo simulation results in which price ($ scallop^{-1}), mortality (% year^{-1}), and spat collection success (spat collector^{-1}) were all modeled as random variables with triangular distributions over 500 runs. A simulation in which all three variables were randomized was also performed. The mean, standard deviation, minimum, maximum, and probability of negative returns are listed. Negative values are displayed in red.

NPV5 (USD):	Random price ($0.7 - $1.30)	Random mortality (2.5% - 24.5%)	Random spat collector^{-1} (300 - 2,700)	Random price, mortality, and spat
Mean	$246,044	$251,655	$247,009	$239,263
Sd	$135,890.46	$14,516	$141,177	$143,780
Minimum	-$65,196	$216,767	-$310,045	-$172,800
Maximum	$568,227	$284,107	$586,608	$569,605
Risk of loss (NPV5<0)	2.8%	0%	3.8%	5.2%

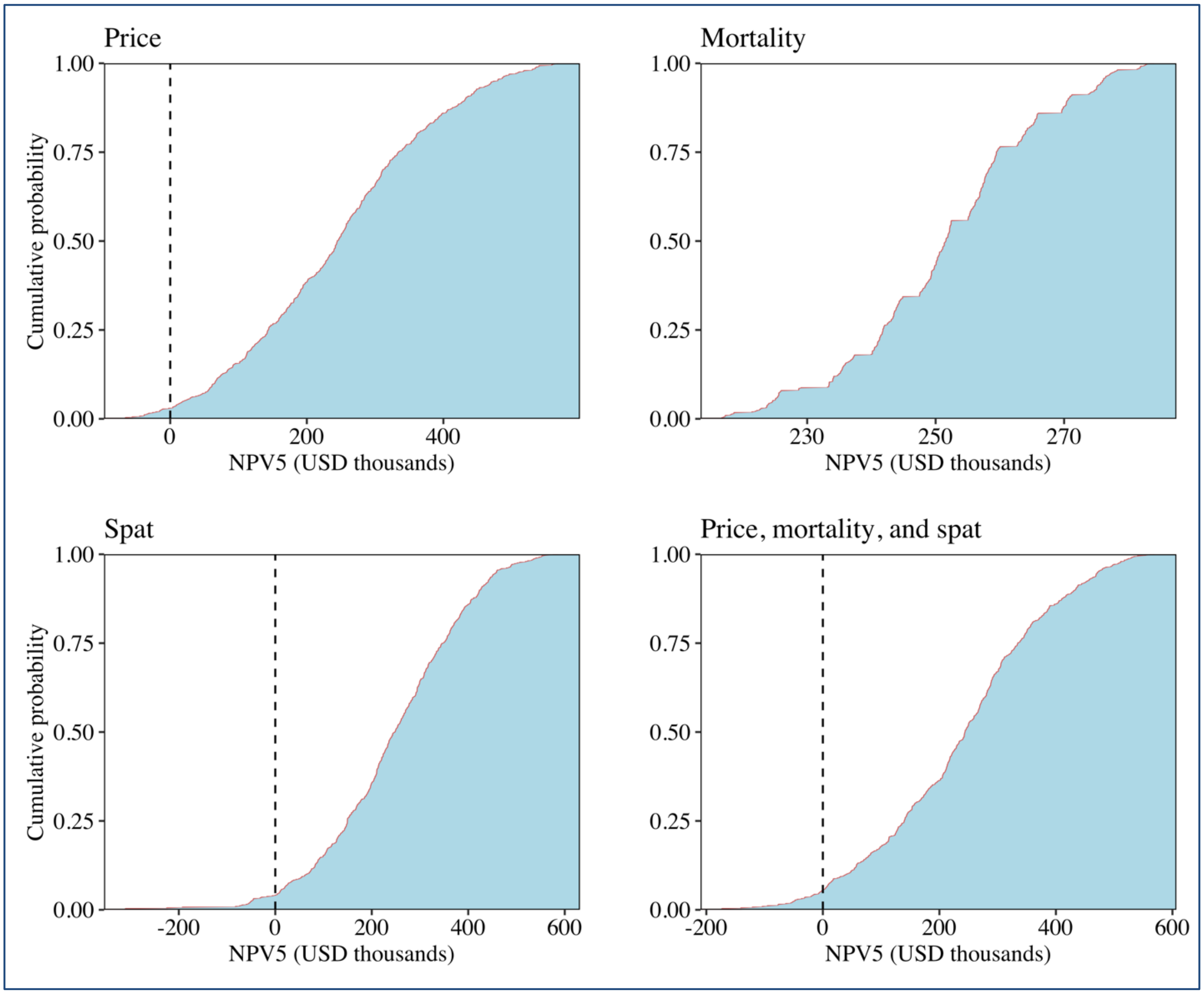


Figure 8. Cumulative probability distribution curves for the results of stochastic Monte Carlo analyses. Market price (top-left), mortality (top-right), spat collection success (bottom-left), and a combination of the three (bottom-right) were modeled as random variables with triangular distributions over 500 runs.

CHAPTER 4

DISCUSSION

Our analysis overwhelmingly points towards the conclusion that increasing cultured scallop production in the Gulf of Maine will require farms to sell whole scallops at scale (>200,000 scallops $year^{-1}$) while keeping labor costs at a minimum. End product type was the most important determinant of farm-level success. The vast majority of farms bringing whole scallops to market were successful while those targeting shucked meats alone generated negative returns. Regardless of end-product type, we observed labor and mechanizations issues associated with lantern nets. Despite the fact that COP was inversely proportional to farm size, labor costs increased linearly with production volume, a function of low density net stocking. Sensitivity analyses, however, shed light on opportunities to overcome many of these challenges. Both time to market and market price exerted the most influence on the NPV5 of whole scallop farms. Increasing scallop growth rates and developing markets for whole scallop products could substantially increase farm values. Similarly, relatively small (5 - 10%) decreases in the time required to handle nets could lead to substantial decreases in production costs. These results, in aggregate, argue for future investment in four primary areas of research: (1) develop methods to mechanize or circumvent lantern net culture, (2) identify "optimal" stocking densities that balance growth and expenses, (3) build site selection tools to optimize scallop growth, and (4) strengthen end markets for whole scallop products while increasing biotoxin testing capacity.

The combination of clear economies of scale and labor bottlenecks likely means that reducing the time required to handle lantern nets is one of the more pressing needs of this burgeoning industry. Our semi-structured interviews corroborate this hypothesis, as all seven participants referenced mechanization, and six referenced biofouling, as a current challenge on their farms (Figure 1). Growers and researchers have made considerable investments in lantern net and scallop washing technology (Morse, 2017) and this equipment is at least partially responsible for the success of our model farms. Improvements to washing equipment or workflow could further reduce labor costs and increase profitability. Yet even with the added benefits of this equipment, we still observed mechanization issues associated with net culture. For example, in all four scenarios labor made up between 30 - 70% of total expenses and this portion increased with farm size. Similarly, small increases in net handling time requirements led to disproportionately large increases in production costs.

One potential solution to mitigate these issues would be to circumvent lantern nets almost entirely. Ear-hanging is an alternative grow-out method that increases growth rates compared to lantern nets or bottom cages and eliminates the costly need to handle heavily fouled equipment after the first year of juvenile culture (Dadswell & Bradford, 1991; Grant et al., 2003; Morse, 2017). Despite the growth benefits, there is still considerable uncertainty surrounding ear-hanging cost requirements. Ear-hanging supports a ~$500 million USD *Patinopecten yessoensis* industry in Japan (OECD, 2020), allowing small family operations to bring a significant quantity of scallops to market each year (Beal et al., 1999; Imai, 1977; Ventilla, 1982). While the specialized drill and pinning machine required for ear-hanging would substantially increase a grower's upfront investment (Coastal Enterprises, Inc., 2019; Morse, 2017), we demonstrate that significantly scaling up production volume with lantern nets has limitations. Future scallop bioeconomic analyses should weigh cost estimates of ear-hung scallops against the estimates generated here. Specifically, under what conditions do the long-term decreases in labor expenses outweigh the initial increase in labor and equipment costs for ear-hung scallops. Until ear-hanging technology has been tested and becomes more available in the Northwest Atlantic, we expect growers will primarily be using lantern nets.

Optimizing lantern net stocking density from both a growth and cost perspective, i.e., balancing time to market with labor and equipment expenses, can potentially maximize farm value. Scallops are particularly sensitive to the effects of space limitation and food depletion within nets, and small increases in the number of individuals per net tier can significantly increase time to market (Coleman et al., 2021; Parsons & Dadswell, 1992). Farm expenses are a function of stocking densities as well, as the number of nets a grower must manage dictates labor, capital, and equipment costs. Handling-related mortality can be a significant issue for cultured scallops compared with other species of bivalves (Dadswell, 1989; Grecian et al., 2000, Coleman et al., *under review*). As opposed to the more efficient "batch processing" method for grading and cleaning oysters or mussels, growers must move from net to net and minimize the time scallops spend out of the water. We observed that increasing production volume (and thus the number of nets a grower must handle) resulted in mounting labor costs. Additionally, lantern net depreciation made up nearly 10% of all costs for the 600K farm in scenario 1. The stocking density values we assumed in our model are based on the requirements to bring scallops to market size in 19 months. If we artificially increase the grow-out density from 15 to 25 individuals $tier^{-1}$ for the 600K farm in scenario 1, and still assume 19 months to market, NPV5 increases from $255,210 to $395,344. Just as decreasing the time required to handle a single net during grow-out by 5 mins resulted in a $0.04, or ~6%, reduction in cost of production, small reductions in stocking density can have similar effects. Others have explored the nested effects of farm (Pilditch et al., 2001) and individual net (Parsons & Dadswell, 1992) stocking densities on growth, but our results argue for explicitly analyzing density within the framework of a cost benefit analysis. Identifying the specific densities at which growth is maximized and costs are minimized is one strategy for growers to reduce production costs.

Careful site selection is another method of improving farm value by increasing growth rates without needing to further reduce net stocking densities. Increasing the time required to bring whole scallops to market size by 25% (~5 months) decreased farm value by nearly $200,000 for the 600K farm in scenario 1. It is clear that optimal scallop site selection will require a multivariate approach. Temperature exerts a nonlinear influence on scallop growth with an optimum between 10 - 15 °C (Coleman et al., 2021; Davidson & Niles, 2014; Stewart & Arnold, 1994) and food availability and quality ultimately facilitate increases in scallop biomass (MacDonald & Thompson, 1985; Pilditch & Grant, 1999). Food conditions also have stocking density implications, as high food environments could potentially allow growers to increase the number of scallops in each net tier and still achieve marketable growth (Côté et al., 1994). Identifying lease sites within optimal environmental ranges is only one criterion that prospective growers of any aquacultured species must consider (Johnson et al., 2019). Specifically, we demonstrate that operating a profitable farm scallop will require significant space to account for low density net stocking. Interview participants repeatedly stressed the importance of holding longlines below high wave energy levels (Khandekar & Swail, 1995) to avoid mortality or decreased growth (Freites et al., 1999), underscoring the need for adequate depth. Siting farms in areas with optimal environmental conditions as well as adequate depth and space for net culture can have significant economic benefits. Developing site selection tools that take into account multiple social and biophysical parameters, particularly any potential multi-use conflicts (Radiarta et al., 2008), will be critical to effectively grow the industry.

The most important determinant of profitability was ultimately end product type. Even with the added benefit of an owned vessel and equipment sharing (scenario 4), selling shucked meats alone generated negative returns. For these businesses, the period between initial capital outlays and cash inflows was long (4+ years) and holding scallops at 5 individuals $tier^{-1}$ in lantern nets led to insurmountable labor and capital costs. Under current production conditions, farms will likely be required to sell at least a portion of their inventory into the live market. However, selling whole scallops poses considerable challenges. Growers and researchers in Maine have worked diligently with the Maine Department of Marine Resources (DMR) to sell live products (Maine Department of Marine Resources, 2017), but the testing costs are considerable for small operations in the pre-revenue period and biotoxin closures could significantly impact revenues. ASP and PSP abundance varies spatially and temporally in the Gulf of Maine (Cembella et al., 1994; Keafer et al., 2005; Luerssen et al., 2005), making proactive site selection an unlikely strategy to completely avoid issues with toxins. However, as whole scallop sales continue to increase, managers and researchers should incorporate historical *in-situ* scallop biotoxin data into site selection tools. Lending prospective growers insight into the potential timing and extent of closures in a given area will allow them to better plan for disruptions to whole scallop sales, a critical component to farm-level success.

Increasing the value of novel whole scallop products within a competitive seafood market will require investing in both the necessary testing to satisfy public health requirements in parallel with the consumer education and distribution networks. Market prices exerted the most influence on the profitability of farms selling whole scallops, indicating that future changes in supply or demand could have adverse effects. A market analysis of farm raised scallops indicated that live products from Maine could be well received by chefs, retailers, and distributors (Coastal

Enterprises, Inc., 2019). Recent research also demonstrates that consumers may be less averse to consuming farmed shellfish compared with farmed finfish (i.e., salmon, tilapia, etc.) resulting in higher willingness to pay (Brayden et al., 2018). Scallop adductor muscles form the basis of a ~$1 billion industry in the U.S. (National Marine Fisheries Service, 2020) with nearly half the value coming from imports (Hale Group, Ltd, 2016). Our analysis suggests that unless production methods substantially change (i.e., ear-hanging or improvements to net culture) and a subsequent reduction in production costs is realized, businesses will be unable to cost effectively target the adductor market using lantern nets alone. Investing in end markets, consumer education, and testing capacity for whole scallops in the near term is the most readily available strategy to increase farmed scallop production in the Northwest Atlantic.

Production costs for farms in scenarios 2 and 4 were substantially lower than those for farms in scenarios 1 and 3, indicating that transitioning to scallop aquaculture from a fishing background or co-oping with other growers offers large advantages. A recent analysis of Maine's aquaculture lease holders concluded that, as of 2017, only 0.58% of commercial fishing license holders also held an aquaculture lease (Stoll et al., 2019). The gear requirements for scallop aquaculture (i.e., offshore spat collection, hydraulic lifting capabilities, and adequate deck space for handling lantern nets) included in our model overlap with those of lobster fishing. In fact, two of the seven interview participants hold commercial lobstering licenses and two had previously worked on lobster boats. While we observed high upfront costs required to start a scallop farm, we also note that scallop farming in particular may offer a pathway to realize the coastal diversification potential of aquaculture heralded by policy makers (Mamauag et al., 2013; DMR, 2004). Removing the cost of the vessel and truck generated a significant (~$175,000) reduction in upfront costs during the challenging pre-revenue period. Similarly, equipment sharing through a farmer cooperative not only spreads the cost of specialized equipment across other businesses, but also offers opportunities for sharing labor and expertise. In Japan, scallop aquaculture cooperatives are an integral part of the nation's ~$500 million USD industry (Beal et al., 1999; Ventilla, 1982). Effective transition to aquaculture requires explicit benefits to local communities and limited disruption to existing social patterns (Rubino & Stoffle, 1990). Individuals who have experience working on the water and adopt scallop aquaculture may have both economic advantages and may be able to overcome the social, environmental, and regulatory challenges that are hindering aquaculture-based fisheries diversification in the Northwest Atlantic (Cleaver et al., 2018).

Scallop aquaculture represents a potentially profitable opportunity to sustainably increase U.S. seafood production, offset a substantial trade imbalance, and provide employment opportunities for coastal communities most at risk from climate change. Ensuring that increased scallop aquaculture output realizes not only the economic, but also the societal goals, of equitable coastal development will be critical in effectively increasing the resilience of coastal communities (Krause et al., 2015). Identifying the regulatory conditions under which the economic benefits of scallop farming can be realized in the regions in which farms are sited should be a research priority that accompanies technical and biological R&D. Domestic seafood production is predicted to lag well behind demand in the coming years (Shamshak et al., 2019). As the Gulf of Maine warmed faster than 99% of other marine water bodies on Earth between 2004 and 2013 and continues to warm (Pershing et al., 2015), increasing the production capacity and diversity of the aquaculture sector will play a key role in fostering coastal resilience (Bricknell et al., 2020). Our analysis suggests that scallops could be a potentially lucrative farmed species, but unique collaboration between regulatory agencies, researchers, and industry members will be needed to overcome a diversity of challenges before these goals can be realized.

4.1 Conclusion

Using a bioeconomic modeling approach, we analyzed the performance of scallop farms in the Northwest Atlantic under a variety of technical, biological, and economic constraints. In all scenarios, cost of production was inversely proportional to farm size and businesses selling more than 200,000 whole scallops year^{-1} were profitable. Alternatively, farms selling only shucked meats generated consistently negative returns. We also identified numerous constraints that may hinder further expansion in the Northwest Atlantic, as well as strategies to mitigate these issues. Based on economies of scale, labor bottlenecks, and the influence of end product characteristics, growers will most likely be required to sell at least a portion of their inventory into the "whole" scallop market and increase production volume to account for high overhead costs. Developing multi-criteria site selection tools that take into account biophysical (temperature, food, salinity, depth etc.) and social (space, conflicting uses, etc.) variables can have large positive economic effects on future farms as adequate space for low density net stocking will be required. Industry members will also have to work with regulatory agencies to increase biotoxin testing capacity and ensure the continued safe sale of live products. There are limits to net based scallop aquaculture that could potentially be mitigated through improved mechanization or alternative techniques such as ear-hanging. Major reductions in cost of production would allow growers to potentially target the nearly $1 billion USD adductor muscle market. Scallop aquaculture represents a potentially profitable opportunity to sustainably offset a large domestic seafood trade imbalance and provide benefits for coastal communities if the necessary technical and regulatory challenges can be overcome.

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APPENDIX A: Interview script

R&D Requirements

1. What are the biggest challenges facing sea scallop aquaculture in the Gulf of Maine today?

2. How can the research resources in the state best help to answer these questions and solve these problems?

Participant characteristics

1. What type of aquaculture lease or license do you currently possess (if multiple, include all)?

2. For how many years have you been farming scallops?

3. Do you farm any other species?

4. If so, are these other species grown on the same lease as your scallops?

5. Please specify the number of additional laborers you employ and specify their characteristics (i.e., full time, part time, volunteer, etc.)

6. Where is your home dock or pier?

End Market and Product Specifications

1. Do you sell whole scallops and/or shucked adductor muscle?

2. What type of end markets do you sell to (direct to consumer, wholesale, etc.)?

If shucked meats:

3. What is the size range of scallops that you harvest for the adductor muscle market?

4. Do you shuck these scallops yourself?

5. If not, how do you shuck these scallops?

6. What is the expected unit price for this product?

7. How does this price vary across size classes?

8. What is the expected annual sale (in pounds, pieces, etc.) of shucked meats?

If whole scallops:

9. What is the size range of scallops that you harvest for the whole scallop market?

10. What is the expected price per scallop for each size class?

11. What is the expected total sales of each size class? Please feel free to estimate these numbers in any way that you would like (individuals / year, dollars per season, etc.).

12. How long is the sale period for each year class of scallops? That is, for how many months are you able to sell scallops within a specific size range before they get too large?

Biotoxin testing:

13. How many times per month do you test products for the presence of ASP and PSP?

14. How often are you prevented from selling whole products due to either ASP or PSP levels above the legal limit?

15. What is the price you pay per test?

16. How do you transfer your samples to the appropriate testing site?

Lease Configuration

1. How deep is your site?

2. What is the acreage?

3. What is the configuration of your lease: longline, bottom culture, bottom seeding, etc.?

If longline:

4. How many longlines do you currently have in the water?

5. How long is (are) your line(s) in the horizontal direction?

6. If you have multiple lines, how far apart is each line?

7. How much scope do you use to anchor each line?

8. How much chain do you use at the bottom of each mooring line?

If bottom culture / cages:

9. How many bottom cages do you currently have on your site?

10. How far apart do you space each cage?

11. How do you mark each cage?

Capital expenses

1. Please refer to table 1. We will now go through the list of capital expenditures and decide whether or not you have purchased the item for your farm (Y/N). If yes, please provide some more information on the specifications of the item (i.e., weight and type of anchor, diameter mooring line, lantern net mesh diameter, type of vessel, type of longline floatation buoys, etc.), and the unit cost of the item. Then, please try to estimate the lifespan of the item in years, and, if multiple items, the percentage of the lot that is replaced at that time. Lastly, if the item is used for other purposes (other species, other business, etc.) please estimate the percentage of time dedicated scallop aquaculture.

2. Are there any items missing from table 1? If so, please refer to table 2 and include all the relevant information.

Production schedule: spat collection, grading, stocking, thinning, cleaning

The following interview sections are organized chronologically. The goal is to understand the process of bringing a single year class of scallops to market size. I'm going to start by asking you about your spat collection methods, then your nursery culture (Y1 of grow-out), then your grow-out methods for the following 2 years.

1. With what method do you obtain new spat?

If spat collection:

2. How many spat lines do you deploy per year?

3. How many bags do you deploy on each line?

4. What is the depth, roughly, of the water in which you deploy bags?

5. How far apart do you space bags on each line?

6. In what months do you start deploying spat bags?

7. In what months do you start retrieving spat bags? Do you remove spat from the bags at this time? If not, are the bags held on your lease?

8. What is your expected total spat yield per bag (individuals)?

9. What is, roughly, the average size of the collected spat?

10. For clarity, what is your total estimated spat yield per year?

11. Is all of this spat grown out on your farm?

12. If not, do you sell spat?

If spat purchase:

13. What time of year do you purchase spat?

14. How much spat do you purchase each year?

15. What is the cost of spat?

16. From whom do you purchase spat?

17. What is the estimated size of the spat you purchase each year?

Juvenile culture Y1: **Y1 refers to the 12 months following initial stocking of scallops into enclosures from spat collector bags.**

18. In what months do you initially stock nets or cages with spat on your site?

19. What gear type (nets, cages, etc.) do you use for juvenile culture in year 1 (Y1)?

20. With how many individuals / level (cage) do you initially stock your nets (cages) in Y1?

21. How far apart do you space these enclosures on your line (for nets) or lease (cages)?

22. What is the stocking, grading, and cleaning schedule for Y1 scallops?

23. Do you change nets types at any time over the course of this 12 month period?

24. Do you use any equipment to help with grading, cleaning, or thinning in Y1?

25. What is the expected total loss, percentage wise, over the 12 months from initial stocking in juvenile culture enclosures to stocking into Y2 enclosures?

26. Is there a seasonality to this loss? Are there processes specific to Y1 that cause mortality?

Grow-out Y2: **Y2 refers to the period beginning 12 months from initial stocking of spat into nets or cages and ending 12 months after that time.**

27. In Y2 of grow-out, do you **ear-hang** or use **enclosures** (nets, cages, etc.)?

If enclosures:

28. Are the enclosures you use in Y2 different from those in Y1 in size, type, mesh, etc.?

29. If so, in what months do you begin to transfer scallops into these new nets?

30. With how many individuals / level (cage) do you initially stock these new enclosures in Y2?

31. How far apart do you space these enclosures on your line (for nets) or lease (cages)?

32. What is the stocking, grading, and cleaning schedule for Y2 scallops?

33. Do you change net or cage types at any point during Y2?

34. Do you use any equipment to help with grading, cleaning, or thinning in Y2?

35. What is the expected total product loss, percentage wise, over Y2?

36. Is there a seasonality to this loss? Are there processes specific to Y2 that cause mortality?

If ear hanging:

37. In what months do you start ear-hanging in Y2?

38. How large are your scallops typically once you begin ear-hanging?

39. How many scallops / ear-hanging line do you typically fit?

40. Do you clean scallops before the process?

41. Do you grade scallops before the process?

42. What, if any, special equipment do you use to ear-hang?

43. How far apart on the longline do you space ear-hanging lines?

44. Do you weigh down the bottom of your ear-hanging lines?

45. How often do you clean ear-hung scallops during the course of Y2?

46. Do you use any equipment or machinery to clean ear hung

scallops?

47. What is the expected total loss, percentage wise, at the end of Y2?

48. Is there a seasonality to this loss? Are there processes specific to Y2 that cause mortality?

Grow-out Y3:

If enclosures in Y3:

49. Are the enclosures you use in Y3 different from those in Y2 in size, type, mesh, etc.?

50. If so, in what months do you begin to transfer scallops into these new nets / cages?

51. With how many individuals / level (cage) do you initially stock these new enclosures in Y3?

52. How far apart do you space these enclosures on your line (for nets) or lease (cages)?

53. What is the stocking, grading, and cleaning schedule for Y2 scallops?

54. Do you change net or cage types at any point during Y2?

55. Do you use any equipment to help with grading, cleaning, or thinning in Y2?

56. Do you change net or cage types at any point after thinning during Y3?

57. What is the expected total loss, percentage wise, over the 12 months after Y3 stocking?

58. Is there a seasonality to this loss? Are there processes specific to Y3 that cause mortality?

If ear hanging in Y3:

a. If enclosures in Y2:

59. In what months do you start ear-hanging in Y3?

60. How large are your scallops typically once you begin ear-hanging?

61. How many scallops / ear-hanging line do you typically fit?

62. Do you clean scallops before the process?

63. Do you grade scallops before the process?

64. What, if any, special equipment do you use to ear-hang?

65. How far apart on the longline do you space ear-hanging lines?

66. Do you weigh down the bottom of your ear-hanging lines?

67. How often do you clean ear-hung scallops during the course of Y3?

68. What is the expected total loss, percentage wise, at the end of Y3?

69. Is there a seasonality to this loss? Are there processes specific to Y3 that cause mortality?

a. If ear hanging in Y2:

70. How often do you clean ear-hung scallops in Y3?

71. What is the expected total loss, percentage wise, at the end of Y3?

72. Is there a seasonality to this loss? Are there processes specific to Y3 that cause mortality?

Operating expenses

1. Please refer to table 3 for the following set of questions. Together, we will go through the tasks and try to record the total hours dedicated to each task annually. First, please specify the time unit with which you feel most comfortable describing each task. For example, minutes per net cleaning, days to grade an entire year class, etc. Next, please estimate the time required to complete the task using the units you specified. Finally, please make an annual

time requirement estimate for each task. This should represent the total number of hours, days, weeks, or months, dedicated to each task in total.

2. Please refer to table 4. This table presents a list of operating expenses. We will now go through the list, identify the unit in which you would like to present these expenses (hours / week, total hours per month or year, etc.), estimate the cost per unit, and then estimate the total number of units per year, month, week, day, etc.

Table A1. Capital expenditures and associated lifespans

Item	***In use? (Y/N)***	***Type (specify)***	***Unit***	***Cost / unit***	***Lifespan (years)***	***Rep. %***	***% to scallops***
Anchors							
Horizontal Long Line							
Vertical Mooring Line							
Lease Marker Buoys							
Corner Tension Buoys							
Compensation Buoys							
Boom / Hauler							
Truck							
Star Wheel							
Spat Line Buoys							

Table A1. Continued

Item	*In use? (Y/N)*	*Type (specify)*	*Unit*	*Cost / unit*	*Lifespan (years)*	*Rep. %*	*% to scallops*
Spat Line Anchors							
Spat Bag Mooring Line							
Spat Bags							
Spat Bag Filling							
Lantern Nets							
Pearl Nets							
Bottom Cages							
Scallop Washer							
Scallop Grader							
Bost Customization							
Fish Tote							
Packaging Supplies							
Business computer							
Longline Weights							
Mooring Chain							
High Flyers							
Vessel							

Table A2. Capital expenditures not included in table 1 and their associated unit costs / lifetimes

Item	***In use? (Y/N)***	***Type (specify)***	***Unit***	***Cost / unit***	***Lifespan (years)***	***Rep. %***	***% to scallops***

Table A3. Production tasks and their associated time requirements and frequencies

Task	***Unit***	***Time / Unit***	***Annual Time Requirement***
Spat Bag Deployment			
Spat Bag Retrieval			
Cleaning scallops			
Grading scallops			
Thinning scallops			
Stocking nets/cages			
Ear hanging			
Other			
Other			
Other			

Table A4. Operating expenses and fixed costs

Item	***Unit***	***Price / Unit***	***Count***
Full Time Labor			
Part Time Labor			
Volunteer Labor			
Boat Fuel			
Truck Fuel			
Boat Maintenance			
Truck Maintenance			
Equipment Maintenance			
Boat Insurance			
Truck Insurance			
Crop Insurance			
Business Liability Insurance			
Other			
Other			
Other			
Other			

APPENDIX B: Bioeconomic model parameters

Table A5. Production model parameters

Production model parameters	
Spat bags per line	20
Average spat per collector bag	1,500
Initial juvenile culture stocking density (6mm nets)	200 $tier^{-1}$
Juvenile culture thinning density (12mm nets)	50 $tier^{-1}$
Initial grow out thinning density (12mm nets)	15 $tier^{-1}$
Final grow-out density (scenario 3 only)	5 $tier^{-1}$
Longline spacing	100ft
Lease depth	60ft
Annual mortality	12.5%
Market size (mm)	75
Time to market from 7mm spat (months)	19 - 31
Harvest schedule	Year round

Table A6. Economic model parameters

Labor cost (USD/FTE including benefits, PTO, and payroll tax)	$25.00
Business and startup fees	$1,883.00
Owner debt:equity	50:50
Discount rate	7.5%
Loan characteristics	10 year term, annual repayment schedule, 7.5% interest

Table A7. Depreciable capital items

Item	*Unit*	*Unit Cost*	*Lifespan (years)*
Lantern net: 6mm	Each	$21.67	8
Lantern net: 12mm	Each	$21.67	8
Lantern net dropper lines (11/32")	Foot	$0.07	10
Longlines	Lot	$3,178.93	8
Lease markers (highflyers)	Each	$79.99	15
Vessel (includes hydraulics, jib crane, starwheel (pair), live well, hot tank, and customization for washer and grader)	Lot	$150,000.00	25
Truck	Lot	$23,000.00	7
Scallop washer (includes sump pump, generator, 24-volt battery, washer pump, fabrication and installation)	Lot	$36,123.00	15
Scallop grader (includes shipping, converter, battery, fabrication, and installation)	Lot	$13,643.85	15
Sorting racks	Pair	$75.00	7
Business computer	Single	$800.00	7
Spat line (11/32”)	Foot	$0.07	10
Spat anchors	Each	$5.00	10
Spat bag floats	Each	$20.00	10

Table A8. Longline components

Item	*Unit*	*Unit Cost*	*Lifespan*	*Quantity per line*	*Total cost per line*
Anchor (2-ton granite blocks, includes ring and bridles)	Each	$199.00	8	2	$398.00
Longline (1.25", 8 strand woven nylon)	Foot	$0.91	8	800	$728.00
Mooring line (1.25", 8 strand woven nylon)	Foot	$0.91	8	360	$327.60
Corner tension floats (75 lb., 16" diameter)	Each	$14.99	8	15	$224.85
Compensation floats (75 lb., 16" diameter)	Each	$14.99	8	70	$1,049.30
Negative buoyancy weights (cement buckets)	Each	$4.00	8	94	$376.00
Compensation float and weight dropper lines (11/32")	Foot	$0.07	8	1074	$75.18

Table A9. Operating expenses

Item	*Unit*	*Unit Cost*
Boat Maintenance	Monthly lot	$100.00
Truck Maintenance	Monthly lot	$75.00
Misc. Equipment Maintenance (Pumps, grader, washer, hydraulics)	Monthly lot	$50.00
Misc. Expendable Supplies (Fish totes, coolers, zip ties, tools, power washer, etc.): 1 lot per lantern net	USD / net	$0.10
Boat Fuel	USD / gallon	$2.11
Truck Fuel	USD / gallon	$2.85
Harvesting and packaging supplies	USD / 200 harvested individuals	$0.12
PPE replacement	Lot	$15.00
Spat bags (annual cost)	USD / bag	$2.00
Spat bag filling (annual cost)	USD / sq foot	$0.10

Table A10. Fixed costs

Item	*Annual Cost*	*Notes*
Boat insurance	$9,000.00	6% of the vessel value
Truck insurance	$300.00	
Mooring and Dockage	$2,000.00	
Biotoxin testing*	$7,200.00	Avg. 2 tests / month (4 tests/month in summer, 1 test/month in winter)
Business liability insurance	$500.00	
Accounting fees	$400.00	
Lease rent fees	$100.00	$ / acre

Table A11. Labor tasks and associated rates

Item	*Unit*	*Time*	*Individuals*	*Full time equivalent*
August spat line/bag assembly	Hours per line	1	2	2
Fall spat bag deployment	Hours per line	2	2	4
Winter spat line maintenance	Hours per line	1	2	2
Spring spat bag collection	Hours per line	2	2	4
Spring seed sorting	Minutes per spat bag	20	2	40
Spring seed stocking: 6mm lantern nets	Minutes per net	5	2	10
Fall juvenile thinning/net swap: 12mm lantern nets	Minutes per net	13	2	26
Spring adult grading/cleaning/net swap: 12mm nets	Minutes per net	20	2	40
Fall adult thinning*	Minutes per net	20	2	40
Year round harvest	Minutes per 250 individuals	2	2	4
Spring line installation	Hours per line	6	2	12

BIOGRAPHY OF THE AUTHOR

Struan Coleman was born on December 20, 1996 and was raised on Long island, New York. He graduated from high school in 2015. He then attended Dartmouth College and graduated in 2019 with a Bachelor's degree in Environmental Studies. After graduation, he entered the School of Marine Sciences graduate program at The University of Maine in the summer of 2019. After receiving his degree, Struan hopes to one day work in the aquaculture industry. Struan is a candidate for the Master of Science degree in Marine Policy from the University of Maine in May 2021.