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Developing a bioeconomic framework for scallop culture optimization and product development

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\textbf{ABSTRACT}

Aquaculture is the fastest growing food production sector in the world and is quickly diversifying. In the Northwest Atlantic, interest in sea scallop (\textit{Placopecten magellanicus}) (hereafter scallop) aquaculture has grown substantially. However, technical and economic challenges have hindered industry growth. We conducted bioeconomic simulations for various sized farms that targeted either live “whole” scallops or the shucked adductor muscle “meat.” The majority of farms selling whole scallops were profitable. However, all farms selling meats generated negative returns. Labor made up the greatest portion of costs in model simulations and increased linearly with farm size, representing a significant bottleneck. Whole scallop farm value was most sensitive to changes in (1) market price and (2) time to market. Our analysis suggests four strategies to increase farmed scallop production in the Northwest Atlantic: (1) mechanize low density net culture, (2) optimize net stocking densities, (3) build site selection tools, and (4) invest in consumer education, end-markets, and biotoxin testing for whole scallops. The sector will require a combination of regulatory, industry, and research cooperation to overcome these pressing challenges, but holds the potential to profitably diversify the bivalve aquaculture industry.

\textbf{KEYWORDS}

Bioeconomic model; \textit{Placopecten magellanicus}; product optimization; sea scallops

\textbf{Introduction}

Despite benefiting from 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 $\sim1.7$ million jobs (National Marine Fisheries Service, 2020).
2018). Yet over 70% of the seafood consumed domestically is imported, including the ~20% made up by reimports (Gephart et al., 2019). Furthermore, approximately 60% of the U.S. seafood import volume is farmed (National Marine Fisheries Service, 2020).

Aquaculture is the fastest growing food production sector in the world (FAO, 2020) and has been characterized as a means to sustainably increase production of fish and shellfish without further depleting wild stocks (Gunning et al., 2016; Lester et al., 2018). The U.S. wild Atlantic sea scallop (*Placopecten magellanicus*) (hereafter scallop) fishery is the nation’s fourth most valuable fishery, with landings valued at $572 million USD in 2019 (National Marine Fisheries Service, 2021). However, domestic demand for scallops far outstrips supply and, as a result, the U.S. imports an almost equal value of various farmed scallop products from Asia and South America (Hale Group & Ltd, 2016; OECD, 2020). Recent evidence suggests that consumers would be willing to pay a premium for a U.S. farmed scallop product that is landed daily and available year-round (Atlantic Corporation, 2019; Hale Group & Ltd, 2016). The combination of a substantial scallop import market, despite strong domestic supply, and consumer preferences for locally harvested shellfish (Brayden et al., 2018; Mauracher et al., 2013) represents a significant opportunity for a domestically farmed product to capture a portion of the U.S. scallop market.

Efforts to establish a scallop aquaculture industry in the Northwest Atlantic (eastern U.S. and Canada) began in the 1970s, but in the last four decades development has been stifled by technical and, most importantly, economic 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, Cleaver, 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 the cost-benefit of bringing farmed scallops to market using available equipment is less clear (Claereboudt et al., 1994; Penney & Mills, 2000; Shumway & Parsons, 2016).

Low density net stocking, slow scallop 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, Kiffney, et al., 2021; Parsons & Dadswell, 1992; Penney, 1996). The demands of prolonged (3+ year) time to market can generate high labor and equipment costs for growers (Parsons & Dadswell, 1994). In an analysis of 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 whole 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. 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 (i.e., all soft tissue components and the shell) could be profitable.

Shucked meats comprise the vast majority of scallop products consumed in North America, but only make up ~10% of the total mass of each landed scallop (National Marine Fisheries Service, 2020). Bringing whole scallops to market significantly increases the yield from each individual, but poses 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). 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).

In the last decade, close collaboration between researchers, regulatory agencies, and growers in the U.S. has led to technical and regulatory breakthroughs that could translate to commercial success. 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 cost reductions (Beal et al., 1999; Coastal Enterprises, Inc., 2019; Morse, 2017). 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, the first U.S. sales of live farmed scallops were completed in 2019 (Dana Morse, May 2021, 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 seafood market, the ability of growers to profitability sell meats alone, and the effect of various biological, technical, and market variables on farm level success (Coastal Enterprises, Inc., 2019).

Our primary goal was to analyze the feasibility of, and potential bottlenecks to, the emerging scallop aquaculture industry. We conducted semi-structured interviews with growers to inform a bioeconomic framework. Bioeconomic models are useful tools 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 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. We then used the framework to build an enterprise budget tool useful to both new and established growers (https://maineaqua.org/business-production-plans/). The framework is flexible and can be updated as new data or production techniques become available. 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.

Methods

We conducted semi-structured interviews with seven scallop farmers in Maine, USA. Interviews lasted between 1 and 2 hours and were conducted 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, operating, and investment 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 the Supplementary material.

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 potential scallop growers are focused on other species (oysters, mussels, or kelp), experimenting, or growing scallops at a very small, sub-commercial, 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 experience among participants ranged from 2 to 8 years (mean = 4 years). Growers were distributed from southern Maine to the "Downeast" region (the portion of the Maine coast situated North and East of Penobscot Bay), 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
considerable time to the industry and had only recently transitioned to a different species.

Based on the data obtained through the semi-structured interviews with industry leaders, we were able to parameterize a scallop aquaculture bioeconomic model. This spreadsheet-based cash flow model was built in Microsoft Excel® (version 16.53). The model had a 10-year timeline and was used to examine four distinct production scenarios: (1) a business targeting a whole 75 mm scallop; (2) the same business in scenario (1), but with the cost of the boat and work truck removed—which is representative of fishermen who have transitioned to scallop aquaculture and already own equipment; (3) a business exclusively targeting the traditionally consumed shucked adductor “meat” with all costs included; and (4) the same business as scenario (3) but with the cost of the boat and truck removed. For scenarios 2 and 4, we also assumed that the upfront costs of two pieces of specialized equipment included in all scenarios, a scallop washer and grader, were distributed evenly between nine other growers. This cooperative model of equipment and resource sharing has been demonstrated successfully by scallop aquaculturists we spoke with in Maine (Walsh, 2020) as well as others aquaculturists globally (Ankrah Twumasi et al., 2021).

Production tasks on scallop farms can be divided into three distinct stages: spat collection, juvenile culture, and final grow-out (Figure 1). 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 (5 individuals tier\(^{-1}\)) in the fall of the third year 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 (Figure 1). 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 wild scallop fishery as a means of size grading. Based on this stocking and handling schedule, growers relayed that an annual mortality rate of 12.5% can be expected, which we used 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 whole 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, we also assume consistent year-round sales in all four production scenarios (i.e., no closures).
Two of the growers we spoke with had experienced biotoxin levels above the legal limit on their sites. Both the timing and the duration of these closures varied, reflecting the unpredictable spatial abundance of biotoxins in the Gulf of Maine (Cembella et al., 1994). One closure period began in August while the other began in January. However, both closures lasted less than two months (Dana Morse, September 2021, pers. comm.). If similar restrictions on sales were to occur on an annual basis within scenarios 1 and 2, revenues could be significantly altered.

Equipment costs were sourced directly from suppliers when not provided during interviews. 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 were included and are therefore unique to 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% interest rate for

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**Figure 1.** Production timeline for farms targeting either whole 75 mm scallops or 15–20 count meats used in the bioeconomic model. Only in year 3 does the process differ between whole scallop and shucked meat farms. In October of year 3, whole scallop farms are starting to bring product to market, while farms selling meats are starting to reduce stocking densities for an additional overwintering.
depreciable assets. The lifespan of depreciable capital items was informed by the relevant experience of growers.

Given the nascent status of the farmed scallop market, farm gate 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 below the historic sale prices received by scallop growers. For scenarios 3 and 4, we used a market price of $10.50 lb$^{-1}$ of shucked scallop meats, the average ex-vessel value for Maine scallops in 2019 (ME DMR, 2020).

The model consisted of two primary components, a biological sub model and an economic cash flow model. The biological sub model calculated monthly sales as a function of production scale and scallop growth rates (the number of months required for scallops to reach market size). Production scale was quantified as the projected annual sales (in number of scallops) from each collected spat year class. Sufficient quantities of spat were thus collected each year, taking into account expected annual mortality (12.5%), to ensure that sales targets were met. Scallops were sold, however, only once the required number of growing months (19 for whole scallops and 30 for scallop meats) had passed for each year class. All scallops from each spat year class were then sold consistently over the 12 months following this time point (i.e., 1/12th of the inventory sold each month).

The economic sub model calculated the net cash flow ($NCF$) of the business as a function of revenues from scallop sales and corresponding expenses. $NCF$ was calculated as:

$$NCF = CIF - COF$$

where $NCF$ was net cash flow, $CIF$ was cash inflow (revenue generated through the sale of either whole scallops or scallop meats) and $COF$ was cash outflow (the sum of all operating and fixed cash costs). Operating cash costs included items such as fuel, labor, and equipment maintenance, while fixed cash costs included items such as debt repayment, insurance, and equipment replacement. A full list of model assumptions is available in the Supplementary material. $NCF$, $CIF$, and $COF$ were calculated for each month within the 10-year model domain, and were then aggregated annually for analysis.

Using $NCF$, $CIF$, and $COF$, we primarily tracked two model outputs, cost of production ($COP$; $\$ scallop^{-1}$) and net present value ($NPV$; $\$), over both 5 ($COP5$; $NPV5$) and 10 ($COP10$; $NPV10$) year timelines. $COP$ was calculated as:

$$COP = \sum_{t=0}^{n} \frac{COF_t}{S_t}$$
where \( n \) was the total number of years (5 or 10) used in the calculation, \( COF_t \) was the cash outflow during a single year \( t \), and \( S_t \) was the quantity of scallops sold during a single year \( t \). COP calculations began at \( t = 0 \) and thus included the initial capital outlay. NPV is the discounted sum of all future cash flows over a period of time, a method commonly used, through discounting, to evaluate a project based on a next best alternative. NPV was calculated as

\[
NPV = \sum_{t=1}^{n} \frac{NCF_t}{(1 + i)^t} + IO
\]

where \( n \) was the total number of years (5 or 10) used in the calculation, \( NCF_t \) was the net cash flow \( (CIF - COF) \) during a single year \( t \), \( i \) was the rate used to discount future cash flows, and \( IO \) was the initial capital outlay in year 0. The initial capital outlay is paid out in the present \( (t = 0) \) and is thus not discounted. We used a 7.5% discount rate and Microsoft Excel’s net present value formula for all NPV calculations.

To quantify the effects of farm size on COP5, we iteratively increased projected 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 production scenario (1–4). Within each of our four production scenarios, we also examined farms of three different sizes: 200,000 (200 K), 600,000 (600 K), and 1,000,000 (1 M) scallops year\(^{-1} \). For each farm, we projected annual \( NCFs \) as well as calculated COP and NPV over 5 and 10 year time periods to estimate both short term and long term success. We then cataloged the cost structure of the 200 K, 600 K, and 1 M farms in scenarios 1 and 3. When we analyzed the cost structure of simulated farms, capital goods were depreciated using a straight-line depreciation schedule with no salvage value. We also calculated the market price needed to “break-even” (\( NPV_5 > 0 \)) for each of the three farms (200 K, 600 K, 1 M) in each scenario.

We performed sensitivity analyses on the 600 K farms in scenarios 1 and 3 (costs of boat and truck included) only. We 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 600 K farm selling meats alone and with the cost of the boat and work truck included, we included a fourth task, the time required to reduce stocking densities and clean nets for overwintering in the fall of grow-out (Figure 1). 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.

A Monte Carlo analysis was performed 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 600 K farm in scenario 1 (whole scallops) and calculated a corresponding NPV5. We assumed that market price, annual mortality rate, spat collection success, and a combination of the three variables were triangularly distributed. We assumed a best, worst, and most likely value for each parameter based on the variability within our interview data. Market price was bound between $0.70 and $1.30 with a most likely value of $1.00, annual mortality was bound between 2.5 and 24.5% with a most likely value of 12.5%, and spat collection success was bound between 300 and 2,700 spat collector\(^{-1}\), with a most likely value of 1,500 spat collector\(^{-1}\). For each iteration, a value (or values) was chosen at random, using Excel’s random number generator, based on the theoretical distribution of each variable.

Results

During semi-structured interviews, growers consistently referenced seven main themes: (1) site selection, (2) spat supply, (3) biofouling, (4) mechanization, (5) biotoxins, (6) end market uncertainty, and (7) scale. Notably, there was an even distribution of references to each theme across the interviews (Figure 2). 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.

We observed clear economies of scale for farms in all four scenarios. Annual sales were inversely proportional to cost of production ($ scallop⁻¹; COP5) (Figure 3). For example, as production in the model increased from 200,000 to 600,000 scallops year⁻¹ in scenario 1, COP5 fell from $1.12 to $0.68 scallop⁻¹ (Figure 3(a)). However, as we continued to increase sales from 600,000 to 1,000,000 scallops year⁻¹, only fell from $0.68 to $0.59 scallop⁻¹. Production costs were substantially higher for farms targeting shucked scallop meats (ranging from $1.73 to $2.77 scallop⁻¹) than for farms targeting whole scallops ($0.52–$1.12 scallop⁻¹) (Figure 3). Removing the cost of the boat and work truck decreased COP5 by 13–34% for farms selling whole scallops and by 16–26% for farms selling shucked meats (Figure 3).

There were notable differences in the performance of farms targeting whole scallops and those bringing meats to market. For whole scallop

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**Figure 3.** 5 year aggregated cost of production ($ scallop⁻¹) for scenarios 1 (a; whole scallops; red), 2 (a; whole scallops; blue), 3 (b; meats; red), and 4 (b; meats; blue) as a function of farm size (annual sales).
farms, an initial capital outlay ($IO$) was followed by two years of negative net cash flows ($NCF$) before positive net returns were realized in year three (Figure 4(a)). However, for farms in scenarios 3 and 4 (meats only), $NCF$s were negative over the entire 10-year model timeline (Figure 4(b)). The upfront costs for meats only farms (scenarios 3 and 4) were significantly higher than those for whole scallop ventures, driven by the lantern net and longline demands of final low density ($5$ individuals tier$^{-1}$) stocking and an extended grow-out process (30 months). For example, the $IO$ for a $600K$ whole scallop farm, in which the cost of the boat and work truck are included, totals $209,900$ (Figure 4(a)). A farm of the same size targeting meats would require an $IO$ of $411,920$ (Figure 4(b)). All farms selling meats only generated negative NPV5 and NPV10 (Table 1).

![Figure 4](image-url)

**Figure 4.** Net annual cash flows for farms in scenarios 1 (a; whole scallops), 2 (a; whole scallops), 3 (b; meats), and 4 (b; meats) with varying production scales. Year 0 represents the initial capital outlay.
Labor made up the greatest portion of total costs for all farms in scenarios 1 and 3 (Figure 5). For the 200 K farm in scenario 1, labor made up 40% of total costs. However, as farm size increased to 1 M, labor costs increased to 61% of the total share (Figure 5(a)). A detailed look at the cost subcategories for the 600 K 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 600 K farms in scenarios 1 and 3, respectively. Regulatory testing for the

Table 1. Net present value (NPV; $) and cost of production (COP; $ scallop⁻¹) over both 5 (NPV5, COP5) and 10 (NPV10, COP10) year timelines for three farm sizes in each of the 4 production scenarios. Values are in USD.

<table>
<thead>
<tr>
<th>Farm scenario</th>
<th>Farm size (annual sales)</th>
<th>NPV5</th>
<th>NPV10</th>
<th>COP5</th>
<th>COP10</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1): Whole scallops: cost of</td>
<td>200K</td>
<td>−$106,559</td>
<td>$177,473</td>
<td>$1.12</td>
<td>$0.70</td>
</tr>
<tr>
<td>boat and work</td>
<td>600K</td>
<td>$255,209</td>
<td>$1,369,913</td>
<td>$0.68</td>
<td>$0.45</td>
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<tr>
<td>truck included</td>
<td>1M</td>
<td>$617,652</td>
<td>$2,562,985</td>
<td>$0.59</td>
<td>$0.40</td>
</tr>
<tr>
<td>(2): Whole scallops: pre-owned</td>
<td>200K</td>
<td>$66,552</td>
<td>$395,264</td>
<td>$0.74</td>
<td>$0.53</td>
</tr>
<tr>
<td>boat and work truck</td>
<td>600K</td>
<td>$428,291</td>
<td>$1,587,703</td>
<td>$0.55</td>
<td>$0.39</td>
</tr>
<tr>
<td>(3): Shucked meats: cost of</td>
<td>200K</td>
<td>−$598,257</td>
<td>$809,552</td>
<td>$2.77</td>
<td>$1.40</td>
</tr>
<tr>
<td>boat and work</td>
<td>600K</td>
<td>−$1,186,500</td>
<td>$1,706,285</td>
<td>$2.15</td>
<td>$1.16</td>
</tr>
<tr>
<td>truck included</td>
<td>1M</td>
<td>$1,958,856</td>
<td>$2,613,1130</td>
<td>$2.03</td>
<td>$1.12</td>
</tr>
<tr>
<td>(4): Shucked meats: pre-owned</td>
<td>200K</td>
<td>−$397,650</td>
<td>−$529,461</td>
<td>$2.05</td>
<td>$1.12</td>
</tr>
<tr>
<td>boat and work truck</td>
<td>600K</td>
<td>−$974,962</td>
<td>−$1,256,677</td>
<td>$1.78</td>
<td>$1.01</td>
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<tr>
<td>truck included</td>
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<td>−$1,557,598</td>
<td>−$1,992,697</td>
<td>$1.73</td>
<td>0.98</td>
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</tbody>
</table>

Figure 5. Cost breakdown for 200 K, 600 K, and 1 M scallops year⁻¹ farms in scenarios 1 (a; whole scallops) and 3 (b; meats).
sale of whole scallops accounted for just over 4% of costs for a 600 K farm in scenario 1. This value does not include any associated transportation expenses (fuel, time, etc.) to a certified testing center as the value could not be generalized 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 6(a)). Break-even was achieved at the lowest market price ($0.58 scallop\(^{-1}\)) for the 1 M scallops year\(^{-1}\) farm in scenario 2, indicating substantial benefits for a fisherman with a boat and truck transitioning into scallop aquaculture. 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 6(b)). A substantial premium for cultured scallop meats

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**Figure 6.** Net present value (NPV5; $) for 200 K, 600 K, and 1 M scallops year\(^{-1}\) farms in scenarios 1 (a; whole scallops), 2 (a; whole scallops), 3 (b; meats), and 4 (b; meats). The dashed horizontal line denotes NPV5 = 0.
only (sale prices of $43.75 and $36.00 lb.<sup>−1</sup> for a 600 K farm in scenarios 3 and 4, respectively) was necessary to achieve NPV5 > 0.

The time required to handle nets before grow-out, compared to seed sorting or handling nets during juvenile culture, had the most significant impacts on COP5 for the 600 K farm targeting whole scallops (scenario 1). For example, for a whole scallop farm, a 25% increase in the time required to reduce stocking densities in the second spring of grow-out resulted in a $0.05 (9%) increase in COP5 (Figure 7(a)). For the 600 K meats only farm (scenario 3), a 25% increase in the time required to reduce stocking densities to 5 individuals tier<sup>−1</sup> in the second fall for an additional year of grow-out resulted in a $0.17 (10%) increase in COP5 (Figure 7(b)).

Whole scallop farm NPV5 was most sensitive to changes in market price and scallop growth rate (Figure 8(a)). 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 8(a)). Increases in farm size exerted the most influence on NPV5 for the 600 K meats only farm, but the effects were strongly negative. A 25% increase in farm size generated a $282,000 decrease in NPV5 for the 600 K farm selling meats alone (Figure 8(b)).

We performed a Monte Carlo analysis using only the 600 K farm in scenario 1 (whole scallops). All farms selling meats alone generated negative returns and would provide little insight into potential “risk of loss” as a

![Figure 7. Effects of changes in key labor input parameters for 600 K scallops year<sup>−1</sup> farms in scenarios 1 (a; whole scallops) and 3 (b; meats) on cost of production ($ scallop<sup>−1</sup>).](image-url)
Figure 8. Effects of changes in key model parameters on NPV5 ($) for 600 K scallops year$^{-1}$ farms in scenarios 1 (a; whole scallops) and 3 (b; meats).

Figure 9. Cumulative probability distribution curves for the results of a stochastic Monte Carlo analysis using the 600,000 whole scallops year$^{-1}$ farm. Market price (a), mortality (b), spat collection success (c), and a combination of the three variables (d) were modeled randomly with triangular distributions over 500 runs.
result of potentially random parameter variability. Similarly, scenario 1 (owner purchases a boat and truck outright) provides the most generalizable estimate of startup conditions. Over 500 iterations, 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 9). Notably, the “worst-case” spat collection conditions produced the lowest NPV5 ($–310,045) compared to the other three scenarios (Table 2).

Discussion

This study attempts to quantify the effects of biological and production parameters on farm-level success within the emerging Northwest Atlantic scallop aquaculture industry. The results of this analysis are applicable to both new and established farmers and can help identify priority research and development (R&D) areas. A market analysis of farm raised scallops indicated that domestically produced live products could be well received by chefs, retailers, and distributors (Coastal Enterprises, Inc., 2019). Recent research also demonstrates that consumers are willing to pay a premium for locally farmed shellfish (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), representing a significant opportunity for a farmed product to capture a portion of the market share.

Our analysis suggests that, based on current production conditions and available technology, growing the cultured scallop sector 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 profitable while those targeting shucked meats alone needed a significant price premium (>36.00 lb⁻¹) to generate positive returns. We also observed substantial reductions in production costs with increases in scale. However, grower interviews and model simulations highlight labor and mechanization issues associated with

Table 2. Stochastic Monte Carlo simulation results in which market price, mortality, and spat collection success were all modeled as random variables with triangular distributions.

<table>
<thead>
<tr>
<th>NPV5 ($)</th>
<th>Random Price ($0.70–1.30)</th>
<th>Random mortality (2.5%–24.5%)</th>
<th>Random spat collector (300–2,700)</th>
<th>Random price, mortality, and spat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$246,044</td>
<td>$251,655</td>
<td>$247,009</td>
<td>$239,263</td>
</tr>
<tr>
<td>Sd</td>
<td>$135,890.46</td>
<td>$14,516</td>
<td>$141,177</td>
<td>$143,780</td>
</tr>
<tr>
<td>Minimum</td>
<td>–$65,196</td>
<td>$216,767</td>
<td>–$310,045</td>
<td>–$172,800</td>
</tr>
<tr>
<td>Maximum</td>
<td>$568,227</td>
<td>$284,107</td>
<td>$586,608</td>
<td>$569,605</td>
</tr>
<tr>
<td>Risk of loss (NPV &lt; 0)</td>
<td>2.8%</td>
<td>0%</td>
<td>3.8%</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

A simulation in which all three variables were randomized simultaneously was also performed. 500 runs were carried out in each trial. Values are in USD.
lantern nets, regardless of end-product type. Despite the fact that cost of production was inversely proportional to farm size, labor costs increased linearly with production volume, a function of low-density net stocking.

Sensitivity analyses shed light on opportunities and technologies to overcome many of these challenges. Both time to market and market price exerted the most influence on the value of whole scallop farms. Focusing efforts on optimizing scallop growth rates and developing markets for value added farmed 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 R&D: (1) develop and test grow-out 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 rates, and (4) strengthen end markets and invest in consumer education for whole scallop products while increasing biotoxin testing capacity.

The combination of clear economies of scale and labor bottlenecks indicates that reducing the time required to handle lantern nets is one of the pressing needs of this burgeoning industry (Figure 2; Morse, 2017). Small increases in net handling time requirements led to disproportionately large increases in production costs, and vice versa. Yet even with the added benefits of improved equipment included in this model (i.e., the automated scallop grader and washer) we still observed mechanization issues associated with net culture. In all four scenarios labor made up between 30 and 70% of total expenses, and this portion increased with farm size.

One potential solution to mitigate these issues for both whole scallop and meats only farms would be to circumvent lantern nets almost entirely via ear-hanging—an alternative grow-out method that supports a ∼$500 million USD *Patinopecten yessoensis* scallop industry in Japan (OECD, 2020). Ear hanging increases growth rates compared to lantern nets 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), allowing small family operations to bring a significant quantity of scallops to market each year (Beal et al., 1999; Imai, 1977; Ventilla, 1982). Despite the growth benefits, there is still considerable uncertainty surrounding ear-hanging cost requirements in the Northwest Atlantic, as the specialized machinery could substantially increase a grower’s upfront investment (Coastal Enterprises, Inc., 2019; Morse, 2017). Future analyses should identify the conditions under which the long-term decreases in labor expenses outweigh the initial increase in labor and equipment costs for ear-hung scallops.
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 within nets (Coleman, Kiffney, et al., 2021), and small increases in the number of individuals per net tier can significantly increase time to market (Coleman, Cleaver, et al., 2021; Parsons & Dadswell, 1992). Yet the number of nets a grower must manage dictates labor and equipment costs, and emerged as a particularly sensitive parameter within our model simulations (Figures 7 and 8). Others have explored the nested effects of farm (Pilditch et al., 2001) and individual net (Parsons & Dadswell, 1992) stocking densities on scallop growth, but our results argue for analyzing density within the framework of a cost-benefit analysis. Identifying the specific densities at which growth is maximized and costs are minimized will require accurate estimates of the relationship between food availability, net densities, and growth, and should be a future research priority.

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 (NPV5) by nearly $200,000 for the 600 K whole scallop farm (Figure 7). It is clear that effective scallop site selection will require a multivariate approach, including considerations of temperature, food availability, spat collection, and water depth (Coleman, Kiffney, et al., 2021; Côté et al., 1994; Davidson & Niles, 2014; Freites et al., 1999; Khandekar & Swail, 1995; MacDonald & Thompson, 1985; Pilditch & Grant, 1999; Stewart & Arnold, 1994). Our analysis underscores the importance of developing site selection tools that take into account multiple biophysical and social parameters (Johnson et al., 2019), as these factors can exert an outsized influence on financial performance.

The most important determinant of profitability was ultimately the end product type. Even with the added benefit of an owned vessel and equipment sharing, selling shucked meats alone generated negative returns (scenario 4). 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 (Gilbert & Cantin, 1987). 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 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 (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 could incorporate historical in-situ scallop biotoxin data into site selection tools. Insight into the potential timing and extent of closures in a given area will allow growers to better plan for disruptions to whole scallop sales.

Maximizing the value of novel whole scallop products within a competitive seafood market will require investing in consumer education and end markets in parallel with the necessary testing to satisfy public health requirements. Farm gate market prices exerted the most influence on the profitability of farms selling whole scallops. Our model simulations indicated that farms selling >200,000 whole scallops year\(^{-1}\) could be profitable (Table 1). This volume of sales would represent a substantial increase in the current U.S. supply of whole scallops. Investing in both market and testing capacity for these products in the near term will be needed to increase demand to match potential increases in supply.

Production costs for farms in scenarios wherein growers already had access to a vessel and truck (i.e., fishermen transitioning into aquaculture) were substantially lower than those for growers with these capital items, indicating that transitioning to scallop aquaculture from a fishing background offers large advantages. While the transition from fishing to farming has been limited across the entirety of the aquaculture industry (Stoll et al., 2019), two of the seven growers we interviewed hold commercial lobstering licenses and two had previously worked on lobster boats. Based on gear requirements, skill set, and social acceptance, scallop farming, in particular, may offer a pathway to realize some of 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. 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 economic advantages and 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).

Similarly, resource sharing through cooperatives not only spreads out the cost of specialized equipment, but also offers other non-monetary benefits (Kaminski et al., 2020). A recent analysis of the Maine Aquaculture Co-op (MAC), the primary scallop aquaculture cooperative in Maine, noted that
members benefit from knowledge and gear sharing, engage in collective
grant writing, and are able to collectively source prohibitively expensive
machinery (e.g., a scallop grader, washer, ear-hanging drill, etc.) (Walsh,
2020). Five of the seven farmers we spoke with are members of the MAC.
We identified a pressing need for either improved mechanization of net
culture or adoption of ear-hanging. Similarly, the need to operate at scale
(>200,000 scallops year\(^{-1}\)) will require an increase in end-market capacity.
Cooperatives such as the MAC can potentially provide the financial, physical,
or human resources to acquire such machinery, increase the visibility
of novel scallops products within seafood markets, and help grow
the industry.

Scallop aquaculture represents a potentially profitable opportunity to sus-
tainably increase U.S. seafood production. Yet it is critical that growing the
industry achieves not only the economic, but also the societal, goals of
equitable coastal development (Krause et al., 2015). Identifying the regula-
tory conditions under which the benefits of scallop farming are felt locally
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 between 2004 and 2013
(Pershing et al., 2015) and continues to warm (Pershing et al., 2021),
increasing the production capacity and diversity of the aquaculture sector
will play a key role in fostering coastal resilience (Bricknell et al., 2021).
Our analysis suggests that scallops could be a potentially valuable farmed
species that successfully diversifies the shellfish aquaculture sector, but a
unique collaboration between regulatory agencies, researchers, and industry
members will be needed to overcome a diversity of challenges.

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