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Stochastic modeling and financial viability of mollusk aquaculture

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ABSTRACT

Compared to finfish and crustaceans, limited attention has been given to the economic modeling and production risk analysis of mollusk aquaculture. Given mollusk aquaculture's sensitivity to environmental factors, understanding production risk and its relationship to production technology and location is critical to firm viability. We modeled production as a function of random elements and performed stochastic risk analysis utilizing Monte Carlo simulation in conjunction with sensitivity analysis and scenario comparison. We applied these methods to compare different equipment systems and production strategies. This paper provides a framework for shellfish risk research that can be applied to various regions and species.

1. Introduction

Globally, mollusks are the third most valuable aquaculture species group with production worth 34 billion USD (FAO, 2020). Numerous shellfish species are farmed across the world, and global production is increasing rapidly (Garlock et al., 2020). Molluscan aquaculture is a relatively passive and extensive form of aquaculture, with limited negative, and at times even positive, environmental impacts (Botta et al., 2020; MacKenzie, 1996). Due to the limited control with the production process in mollusk farming, understanding the risks associated with production can be critical to a farm's success. To illustrate this point, a survey of French oyster farmers showed 37% of farms at risk of closure in the event of any decline in profits (Le Bihan et al., 2013). This is a challenge in an industry with regular moratoriums on harvest due to naturally occurring organisms that cause diseases in humans (Uchida et al., 2017; Love et al., 2021). At a larger scale, Avdelas et al. (2021) show how limited ability to address risk concerns and important factor in explaining the decline in European mussel production. Despite the industry's need for more knowledge, compared to freshwater finfish and crustaceans, limited attention has been given to economic aspects of mollusk production, such as productivity growth and production risk (Botta et al., 2020).

Research that has been conducted on the economic viability of molluscan aquaculture often employed deterministic profitability models with sensitivity analysis used to measure risk (Adams et al., 2001; Tisdell et al., 1993). Sensitivity analysis is a helpful tool to determine which inputs have the greatest effect on profit (van Groenendaal and Kleijnen, 2002). However, deterministic sensitivity analysis assumes variables are well known and can be represented by a single value, which can be inaccurate if inputs are highly correlated. Due to the characteristics of mollusk farming, models that are a function of multiple random elements are better suited for analysis. Little attention has been given to how the profitability of molluscan aquaculture is impacted by stochastic risk elements. An important exception is Chen et al. (2017), who included variability in the mortality rate, market price, and input variables in a study of oyster aquaculture feasibility in Hawaii (Chen et al., 2017).

Stochastic risk analysis can be performed utilizing Monte Carlo simulation in conjunction with sensitivity analysis (Gonzalez-Romero et al., 2014; Hernandez-Llamas et al., 2004; Hernandez-Llamas and Zarain-Herzberg, 2011) or simulation scenarios can be compared (Chen et al., 2017; Clark et al., 2010; Dame, 2018; Kumar and Engle, 2011; Kumar et al., 2016; Kumar et al., 2018). Applications of stochastic sensitivity and risk analysis in the food production literature have included comparisons of production equipment (González et al., 2013; Kumar et al., 2016; Kumar et al., 2018; Engle et al., 2021) and production strategies (Bentley et al., 1976; Hanson et al., 1984; Massey and Williams, 1991).

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The existing literature on stochastic risk analysis in aquaculture provides a starting point for investigating risk associated with molluscan aquaculture,[1] but it is also important to note that shellfish producers face significantly different challenges in terms of risk compared to finfish and crustacean producers. This is due to fundamentally different production technologies. An example of such a difference is with respect to the feed conversion ratio (FCR). FCR is a major component of most existing aquaculture production models and is included for finfish (Abolofia et al., 2017; Kumar and Engle, 2011; Kumar et al., 2016; Kumar et al., 2018; Lipton and Kim, 2007; Nor et al., 2019; Rocha-Aponte, 2020) and crustaceans (Asche et al., 2021a, 2021b; Gonzalez-Romero et al., 2014; Hernandez-Llamas et al., 2004; Naranjo-Páramo et al., 2018); however, as shellfish are filter feeders, no feed component is necessary in the model. Instead, shellfish production is more sensitive to environmental factors such as water characteristics (flow, temperature, salinity, prevalence of planktonic matter, etc.) or cyclones, factors that vary significantly by region. In this sense, shellfish production has similarities to land-based agriculture with uncontrollable inputs such as precipitation, temperature, or storms. In common with agricultural production, risk mitigation measures such as insurance should be considered due to the risk presented by the unpredictability of nature (Chen and Chang, 2005; Williams, 1988; Wilson et al., 2009; Punge et al., 2014).

The model presented in this paper builds upon earlier work on risk impact in agricultural (Bentley et al., 1976; Massey and Williams, 1991) and aquaculture (Chen et al., 2017; Clark et al., 2010; González et al., 2013; Hanson et al., 1984; Kumar et al., 2016; Kumar et al., 2018; Melia and Gatto, 2005; Parker et al., 2020). The model presented in this paper includes stochastic variables that are present in previous aquaculture risk models such as market price (Chen et al., 2017; Kumar et al., 2018), natural mortality (Chen et al., 2017; Kumar and Engle, 2011; Pincinato et al., 2021a, 2021b), temperature (Melia and Gatto, 2005; Melia et al., 2004; Abolofia et al., 2017), and storms (Clark et al., 2010) in addition to other environmental risks that influence mortality, either direct or indirectly, such as salinity levels. A risk mitigation strategy, in the form of crop insurance, is also evaluated.

The model is applied to oyster production in the U.S. Gulf of Mexico. Stochastic risk variables: dockside price, biofouling, change in water temperature, storm events, and high and low salinity events had direct effects on oyster mortality, equipment longevity, labor costs, and sales revenue. Utilizing this information, we analyzed the profitability and stochastic dominance of three equipment systems: floating bags, floating cages, and adjustable longline. We evaluated firm viability under various levels of environmental uncertainty, and the value of the USDA Noninsured Crop Disaster Assistance Program (NAP) for oyster growers as a risk mitigation strategy.

The paper is organized as follows: the next section discusses the environmental risks analyzed and how they were estimated, the three production techniques evaluated in the manuscript, and the NAP insurance program. Then the assumptions of the analysis and application are discussed. Next, the profitability model and risk distributions employed in the analysis are outlined. The last two sections include the results and a conclusion of the findings that outline avenues for future research.

2. Background

As of 2018, oyster aquaculture was the most valuable form of marine aquaculture in the United States, with Atlantic and Pacific Coast states combining to produce over $200 million of oysters annually (USDA, 2018). Oyster aquaculture is a newer industry in the Gulf of Mexico and only dates back to around 2010 (Walton, 2016; Walton et al., 2013), largely due to productive oyster fisheries. Challenges faced by Gulf of Mexico growers differ from the other production regions in the U.S. due to climatic and ecosystem differences.

While the warm waters of the GOM allow oysters to grow more quickly (Ingle and Dawson, 1952); higher temperatures can be detrimental to oyster growth at extreme levels. Oysters can only endure temperatures over 32 °C during a high or low salinity event for a short time (Lowe et al., 2017). Moreover, an oyster's ability to survive a low salinity event is inversely related to the water temperature (Quast et al., 1988; Rybovich et al., 2016). High salinity events can slow the growth of oysters or be fatal, given sufficiently high salinity and/or event longevity (Seavey et al., 2011). In addition to directly causing mortality, high salinity is associated with mortality from disease and predation (Arnold and Berrigan, 2002). Furthermore, warm waters also increase the prevalence of predators, including the oyster drill (Butler, 1985) and encourage the growth of pathogens (Burreson et al., 1994; Soniat et al., 2008).

Floods and tropical cyclones also impact oyster growth and mortality (Berrigan et al., 1991). Beyond changes to salinity associated with storms, off-bottom oysters can be negatively affected by strong currents and excessive wave action. These stressors can cause mortality (Campbell and Hall, 2019) and damage or displace oyster farming equipment (Putnam, 2018).

Biofouling is the accumulation of biological matter on submerged surfaces (Brooks and Waldock, 2009). The organisms that make up this matter compete for the same planktonic food as oysters (Lu and Blake, 1997) and impact oyster growth and survival (Osman et al., 1989). A number of factors can influence biofouling, including tidal change, current strength, equipment type, and labor usage (Adams et al., 2011; Mallet et al., 2009; Moroney and Walker, 1999).

Three different gear types are commonly employed in GOM oyster aquaculture: floating bags, floating cages, and adjustable longlines. Floating bags are mesh bags attached to floats arranged along a longline. Floating cages house up to six of the same mesh bags used in floating bag systems which contain the oysters. Adjustable longlines utilize baskets attached to a longline that can be moved above and below the water's surface. The different gear types have different capital requirements, a feature that has also been shown to impact risk in aquaculture industries (Ankamah-Yeboah et al., 2021).

Price volatility is significant for all seafood products (Dahl and Oglend, 2014: Asche et al., 2015). In addition to standard market shock, price may vary due to environmental events or disease that influence aggregate supply as demonstrated for salmon by Asche et al. (2017) and Oglend et al. (2022), or contamination risks that reduce demand such as Deepwater Horizon's impact on the GOM oyster market (Morgan et al., 2018).

The United States Department of Agriculture (USDA) Noninsured Crop Disaster Assistance Program (NAP) is available to oyster growers and insures against events that result in lower crop yield or the prevention of crop planting, providing an important risk mitigating mechanism (Farm Service Agency, 2019). Eligible causes of loss include natural disasters such as drought, flooding, excessive wind, temperature change, infestation, and disease, where farmers can chose different levels of coverage. Ineligible causes include changes to oxygen level, such as red tide events, market changes, and mismanagement or negligence (Farm Service Agency, 2019).

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[1] There is a significant literature describing production risk in aquaculture with Khan et al. (2018), King et al. (2018) and Theodorou et al. (2020) as some recent examples and similarly, a separate literature investigating prices and reputational risk with Asche et al. (2017), Bloznelis (2018), Asche et al. (2019), Dahl et al. (2021), Asche et al. (2021a, 2021b), Landazuri-Tveteraas et al. (2021), Fernández-Polanco et al. (2021) and Salazar and Dresdner (2021) as recent examples.

3. Methodology

3.1. Baseline assumptions

Assumptions employed in the analysis were based on published research on oyster aquaculture production in the GOM and the mid-Atlantic (Davis et al., 2013; Dame, 2018; Walton et al., 2013a.; Maxwell and Supan, 2010; Simon et al., 2019; Hensey, 2020; Hudson, 2019; Lowe et al., 2017; Rybovich et al., 2016; Dame et al., 2018) as well as a survey of twelve Gulf growers conducted by University of Florida Institute of Food and Agricultural Sciences (UF IFAS) extension specialists in 2017 and consultation with four shellfish aquaculture extension specialists in 2019 and 2020, Table 1. Production was assumed to take place on a 1.5-acre lease site, which has become a standard lease size in the state of Florida (Florida Shellfish Aquaculture, 2020). Ten-millimeter triploid seed is planted from March until August and has a 12-month grow-out period.[2] The model assumes that all oysters are sold into the half shell market.

Capital and equipment costs were estimated based on input from shellfish aquaculture extension specialists located in the GOM region. Regarding equipment needs and equipment pricing, data was provided by three GOM regional oyster aquaculture equipment suppliers in 2019. The cost of labor was assumed to be $13 per hour for management and $9 per hour for additional manual labor. In 2013, the Virginia Cooperative Extension, VCE, provided estimates for required labor at differing levels of off-bottom oyster production obtained through surveys from 2008 to 2011 (VCE, 2013). We used these data to model labor per week as a function of oysters planted in a given year as shown in Eq. (1).[3]

$$Labor\ hr = -9.552e^{-10}x^2 + .007x + 829.801 \tag{1}$$

The first 40 h per week received management wages, $13, and labor over 40 h per week received $9 per hour. The number of hours predicted per week was then multiplied by an equipment type multiplier, as shown in Table 1, to account for different labor requirements associated with each production technique.

The base insurance coverage is triggered when at least 50% of a farmer's crop value is lost. The value lost beyond 50% of the total inventory value is multiplied by the package price level. In the case of the base package, that is 55 cents on the dollar. As an example, if a farmer lost $60,000 of their total $100,000 inventory, their insurance payout would be 10,000 * $0.55 = $5500. The cost of the base coverage is a flat $325 administrative fee.

For a premium, coverage can be increased. Coverage can be bought up in 5% intervals, from the basic 50% level to 65%. The price level can also be bought up from 55% of product value covered to 100%. This paper includes two premium levels: 1) 50% coverage/ 100% price 2) 65% coverage/ 100% price. Using the example of $100,000 inventory and $60,000 loss, the insurance payouts for the two plans would be: 1) 10,000 * $1.00 = $10,000, and 2) 25,000 * $1.00 = $25,000, respectively.

The annual payment formula is: Administration Fee + (Maximum Coverage * Coverage Level * 0.0525). For the buy-up option, the producer must choose a maximum coverage amount. If a farmer chose to ensure a maximum of $50,000 of their inventory at the 65% coverage level the insurance cost would be, 325 + (50,000 * 0.65 * 0.0525) = $2031.25.

Capital expenditures, excluding a boat, were assumed to be self-financed. This assumption was based on input from shellfish aquaculture extension specialists who indicated that many GOM oyster farmers self-finance their operations due to lack of access to credit.[4] The analysis assumes a gradual ramping of oyster production to match general industry practices. The first-year planting of 105,000 oyster seed was selected to match the state of Florida's minimum annual planting requirement of 70,000 oysters per leased acre. Net present value (NPV) calculations employed a 4% discount rate.[5]

3.2. Stochastic simulations

The software Simetar was used to evaluate risks through Monte Carlo simulations (Richardson et al., 2005). Stochastic simulations measuring profit over a 10-year time frame were run. Twenty-seven scenarios were created to compare the different equipment systems with varying levels of environmental risk, and insurance coverage. One-thousand simulations were run for each scenario. Environmental risks evaluated included high and low salinity events, high and low salinity events combined with high water temperatures, and tropical cyclones. Each environmental risk event had an associated effect on oyster mortality, equipment/capital costs, and labor.

The likelihood of each environmental event occurring ranges from no risk to 150% of the likelihood of each event occurring in Cedar Key, Florida, based on historical occurrence rates.[6] Observational data from 2002 to 2019 was used to estimate the likelihood associated with each event. The parameters for an environmental event are described in Table 2.

3.3. Model

Revenue is determined monthly, where t represents the month. Annual revenue is the summation of the previous 12 months of revenue.

$$E[Revenue_{Annual}] = \sum\nolimits_{t-12}^{t} E[Revenue_t];\ t-12 \geq 0 \tag{2}$$

The expected revenue per month is a function of price, quantity, and any insurance payout collected. P_{DS} is the dockside price per oyster and is a random variable with an average of $0.45. The natural mortality of an oyster crop, including the effects of biofouling, is calculated twice per oyster crop, once after their initial planting, and once applied prior to sale. $Natual_M$ represents this mortality rate and takes a value between zero and one but differs depending on the gear used, as seen in Table 1. Per discussions with GOM shellfish aquaculture extension specialists, on average, 90% of oysters that reach market size can be sold into the half

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[2] Two-thousand five-hundred seed are initially planted into 4 mm mesh bags and thinned by half after 4–6 weeks. Eight to ten weeks after planting, oysters are replanted at a density of 600 oysters per 9 mm bag. The final grow-out starts after 14–24 weeks. Floating Bags and Floating Cages have a density of 200 oysters per 14 mm mesh bag while adjustable Longlines have a grow-out density of 100 oysters per basket.

[3] GOM shellfish aquaculture extension specialists provided labor requirement estimates for low and moderate levels of production that were similar to those outlined in VCE, 2013. Given this overlap and a lack of data on GOM labor requirements for higher levels of production we assumed Gulf labor requirements would increase with production similarly to Virginia production.

[4] The boat was assumed to be financed at 7.5% with a seven-year loan period (equivalent to the terms of a Small Business Administration 7(a) Loan. A work truck was not included in the capital costs as it was assumed a new grower would already have a truck per discussions with industry members.

[5] The NOAA Fisheries - Fisheries Finance Program (FFP) provides aquaculture operators with long term fixed rate financing set at the corresponding loan term's U.S. treasury rate plus two percentage points (NOAA Fisheries, 2021). As of 11/01/21 the FFP rates on 10, 20, and 25 year loans were 3.58%, 4.01%, and 4.00%, respectively (U.S. Department of the Treasury, 2021). The US SBA 7a loan program was used to determine the boat loan rate because the 7a loan program is easier for new small businesses to access than the FFP due to less stringent requirements and shorter loan terms, but the FFP was deemed to better represent the discount rate associated with aquaculture businesses with the treasury rate measuring the risk-free discount rate and the two percentage points serving as an industry risk premium.

[6] Cedar Key is being used as a proxy for the broader GOM due to the area's success with clam aquaculture and a developing oyster aquaculture industry.

Table 1
Equipment system characteristics.

Assumption	Floating Bags	Floating Cages	Adjustable Longline	Source
Max Capacity (oysters/year)	325000^{1,2,4}	320000^{1,2,4}	267000^{1,3}	1. GOM Shellfish Aquaculture Extension Specialists; 2. IFAS GOM grower survey; 3. Davis et al., 2013; 4. Dame, 2018
Initial Capital Cost (105,000 oysters operation)	\$16,614^{1}	\$25,147^{1}	\$42,873^{1}	1. GOM Shellfish Aquaculture Extension Specialists
Variable Cost of Equipment (Ve)	\$0.16^{1,2,3}	\$0.24^{1,2,3}	\$0.27^{1,3}	1. GOM Shellfish Aquaculture Extension Specialists; 2. IFAS GOM grower survey; 3. Walton et al., 2013 a.
Steady State Annual Depreciation	\$14,309.28^{1,2}	\$14,336.69^{1,2}	\$11,973.95^{1,2}	1. GOM Shellfish Aquaculture Extension Specialists; 2. IFAS GOM grower survey
Labor	$\times^{1,2}$	$2 \times^{1,2}$	$0.63 \times^{1,3}$	1. Walton et al., 2013 a; 2. Simon et al., 2019; 3. Davis et al., 2013
Average Natural Survival Rate	88%^{1,3}	91%^{1,3,4}	81%^{2,3,4}	1. Simon et al., 2019; 2. Davis et al., 2013; 3. Walton et al., 2013b; 4. Hensey, 2020

Table 2
Environmental event thresholds.

Event	Threshold	Duration
Storm	>40 mph avg. for 1 h	>1 occurrence per month
High Salinity	>30 ppt avg. per day	>5 occurrence per month
Low Salinity	<10 ppt avg. per day	>2 occurrence per month
High Water Temperature	>90 °F avg. per day	>2 occurrence per month

shell market, the remaining 10% are unmarketable due to malformities that make them unfit for the half shell market. After determining the monthly revenue from oyster sales, any insurance payouts are added to reach a final monthly revenue.

$$E[Revenue_t] = E\left[P_{DS,t}\right]^{*}Natural_{M,12,t}{}^{*}E\left[Q_{12,t}\right]^{*}Sellable_t + I_t; \tag{3}$$

Natural Mortality occurs in $a = 2$ *and* 12

The total cost is a function of labor costs, capital costs, fixed costs, equipment depreciation, and insurance fees ($I_{fee,\ t}$) and is displayed in Eq. (4). Fixed costs include lease fees, certification and licensing costs, fuel, and loan payments. Worker wage and labor in hours are represented by w and L, respectively. v_e is the variable cost of equipment per oyster above current production capacity. v_o is the variable cost for any single-use equipment and seed, which is also the steady state variable cost per oyster once full production capacity has been reached. K is the total value of equipment.

Further costs are accrued if there is a disaster event. The same dummy variables are used from Eqs. (9)–(11) to determine an event occurrence. Subscripts of k and L for disaster variables (High, Low, Storm) denote whether the random variable is for labor or capital costs.

$$\begin{aligned}E[TC_t] = {} & (GearType^{*}w_tL_t) + FC_t + \left(Q_{Planted,t}{}^{*}v_o\right) + \left(Q_{excess,t}{}^{*}v_e\right) \\ & + (Depreciation_t) + I_{fee,t} + K_t\left(Storm_{Dummy,t}{}^{*}Storm_{k,t} + Low_{Dummy,t}{}^{*}Low_{k,t}\right. \\ & \left. + High_{Dummy,t}{}^{*}High_{k,t}\right) + w_tL_t\left(Storm_{Dummy,t}{}^{*}Storm_{L,t} + Low_{Dummy,t}{}^{*}Low_{L,t}\right. \\ & \left. + High_{Dummy,t}{}^{*}High_{L,t}\right)\end{aligned} \tag{4}$$

$$K_t = Q_{planted,t}{}^{*}v_e \tag{5}$$

Disaster insurance covers most disaster events that could affect an oyster farm, excluding changes to oxygen levels. As seen in Eq. (6), the insurance payment is only received if losses total more than the trigger value. This value is calculated based on estimated oyster size at the time of the event.

$$I_t = \left[Value_{Lost,t} - \left(I_{trigger}{}^{*}Value_{Total,t}\right)\right]^{*}I_{rate}; \tag{6}$$

$$given\ Value_{Lost,t} > I_{trigger}\left(Value_{total,t}\right)$$

If a disaster event causes losses exceeding the trigger value, the corresponding payout is determined by the difference between the value lost and the trigger value, then multiplied by the farmers' insurance rate.

The expected quantity of oysters for any age at any given time is expressed as $Q_{a,\ t}$. The number of oysters can be found by subtracting losses due to storms, high salinity, and low salinity, from the previous periods stock, one month younger.

$$E\left[Q_{a,t}\right] = Q_{a-1,t-1} - High_{M,t} - Low_{M,t} - Storm_{M,t} \tag{7}$$

For oysters of age 2, an additional mortality event is included, shown in Eq. (8). Natural mortality is tallied at two and twelve months. Age 12 oyster natural mortality is accounted for in Eq. (3).

$$\left[Q_{2,t}\right] = Q_{1,t-1} - High_{M,t} - Low_{M,t} - Storm_{M,t} - Natural_{M,t} \tag{8}$$

The expected losses to the stock, Eqs. (9)–(11), are determined by multiplying the ending stock of the previous period by the corresponding disaster event dummy variable to determine if an event did occur. If an event did occur, then this product is multiplied by the mortality rate associated with that disaster at that time. Eqs. (9)–(11) are similar but have different starting quantities. This difference is due to not knowing which disaster occurred first given a circumstance where more than one environmental event occurred in a single month. To avoid double or triple counting, losses are subtracted from the total starting quantity before calculating the losses for an additional disaster event. This model has the events ordered as follows: High Salinity, Low Salinity, then Storm. This does mean the model has the potential to overestimate losses due to high salinity while underestimating the losses due to storms.

$$E\left[High_{M,t}\right] = Q_{a-1,t-1}{}^{*}High_{Dummy,t}{}^{*}High_{rate,t} \tag{9}$$

$$E\left[Low_{M,t}\right] = \left(Q_{a-1,t-1} - High_{M,t}\right)^{*}Low_{Dummy,t}{}^{*}Low_{rate,t} \tag{10}$$

$$E\left[Storm_{M,t}\right] = \left(Q_{a-1,t-1} - High_{M,t} - Low_{M,t}\right)^{*}Storm_{Dummy,t}{}^{*}Storm_{rate,t} \tag{11}$$

3.4. Distributions

Random variable distributions employed in the simulations are displayed in Table 3. The parameters were informed by the existing literature and the GOM grower survey, best estimates were made in cases of conflicting information. All disaster event dummy variables are binomial. They are determined by setting an empirically supported likelihood threshold between zero and one. If a randomly selected number pulled from a uniform distribution between zero and one is lower than or equal to the threshold, the dummy takes the value of one, otherwise

Table 3
Variable distributions.

Variable	Distribution	Mean	Mode	Min	Max	Source
Oyster Price	Beta	$0.45	$0.41	$0.30	$0.80	Grice and Walton, 2019; Hudson, 2019
% of product fit for the half-shell market	Triangle	90%	90%	85%	95%	GOM Shellfish Aquaculture Extension Specialists
High salinity mortality rate	Triangle	10%	10%	0%	20%	Dame et al., 2018
High Temp & High Salinity mortality rate	Triangle	30%	30%	20%	40%	Lowe et al., 2017; Rybovich et al., 2016; Dame et al., 2018
Low salinity mortality rate	Beta	15%	1%	0%	88%	Dame et al., 2018
High Temp & Low Salinity mortality rate	Beta	37%	30%	5%	100%	Rybovich et al., 2016; Dame et al., 2018
Storm mortality rate	Beta	9%	1.50%	0%	50%	Putnam, 2018; Dame et al., 2018
High salinity equipment damages	Triangle	13%	10%	0%	30%	Dame et al., 2018
Low salinity equipment damages	Triangle	0%	0%	0%	0%	Dame et al., 2018
Storm equipment damages	Triangle	20%	0%	0%	60%	Putnam, 2018; Dame et al., 2018
High salinity labor	Triangle	25%	26%	20%	30%	Dame et al., 2018
Low salinity labor	Triangle	6%	4%	0%	15%	Dame et al., 2018
Storm labor	Triangle	32%	34%	18%	43%	Dame et al., 2018

zero. The likelihood of an event occurring was calculated by fitting a distribution to empirical data. We then ran 1000 simulations, inspecting how often the numbers pulled from the simulation met the event criteria.

4. Results

4.1. Gear type

When no environmental risk was introduced, all three gear systems were profitable on an annual basis by the end of the 10-year time frame. By year 6, all gear systems had reached their respective maximum production. Profit for year 6 and NPV can be seen in Figs. 1 and 2, respectively. Floating bag production had the highest profit and NPV of the three gear types followed by adjustable longlines and then floating cages. Floating cages were the only gear type to have a negative mean NPV in the no environmental risk scenario. Using the Kruskal Wallis test, holding all other variables equal, we found that gear type had a statistically significant impact on NPV, Table 4. When checking for stochastic dominance, we found floating bags to be first and second order stochastically dominant over floating cages and adjustable long lines. Further, adjustable long lines had first and second order stochastic dominance over floating cages.

Annual cash position by equipment type is displayed in Fig. 3. Floating bags are the most profitable and reach a positive cash position faster than any other gear type. Adjustable longlines have the lowest long-term cost of production and require less labor. Floating cage production, despite having the highest survival rate modeled, does not appear to be an economically sustainable production method given the assumptions used.

To check these finding we employed sensitivity analysis, Table 5. Using year 6 profit for floating bags as the output variable, we changed the inputs that varied by equipment type in addition to market price and wages. Profit was most sensitive to changes in oyster survival rate. This may seem to contradict the scenario comparison, but the differences in survival rate between equipment types were much smaller than the maximum change in the sensitivity analysis. This is an important finding as it shows that while the difference in survival rate among the equipment systems analyzed in this paper was outweighed by other variables, if there was a large enough change in oyster mortality, it would have a major impact on profit and viability.

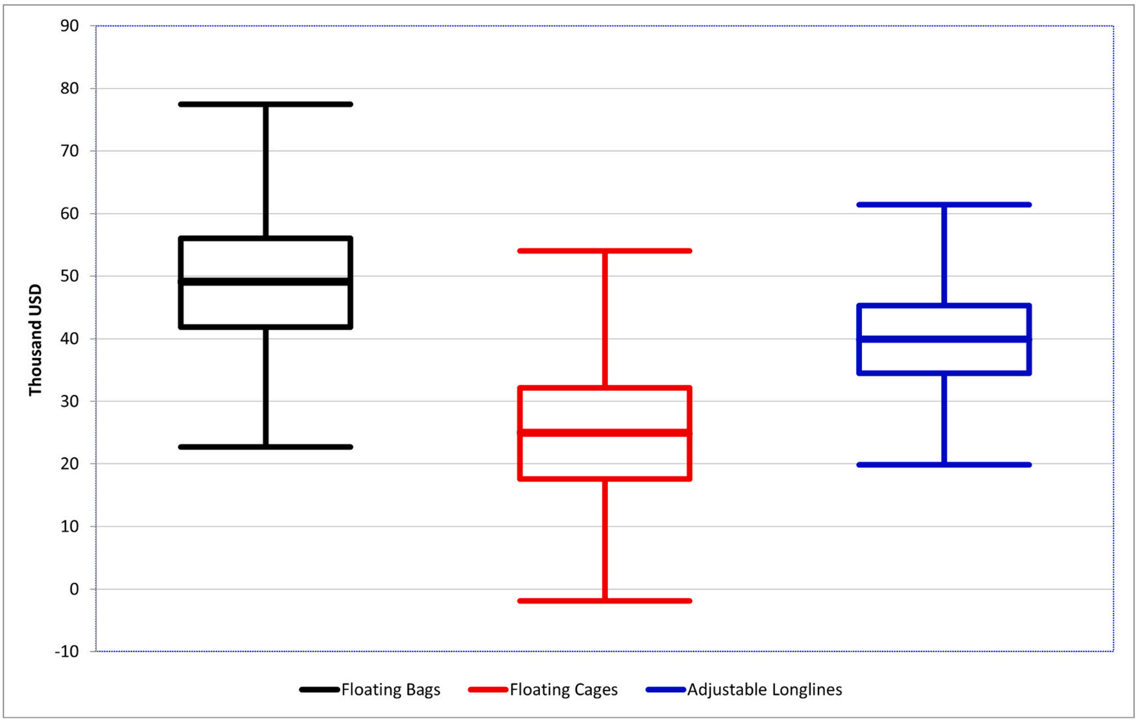

Fig. 1. Steady state profit across gear types with no environmental risk or insurance.

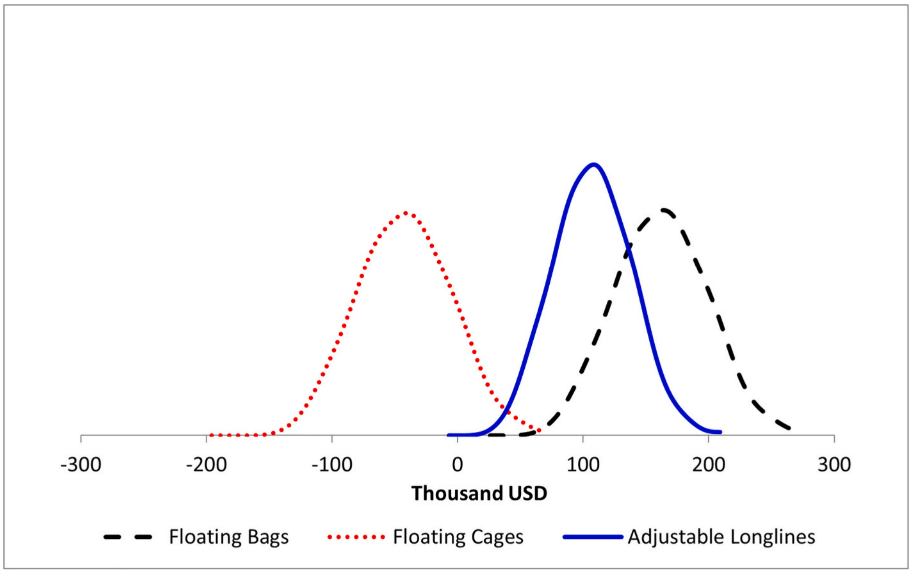

Fig. 2. PDF of NPV across gear types with no environmental risk or insurance.

Table 4
Kruskal Wallis test, non-parametric test of medians.

Exogenous Variable	Endogenous Variable	Scenario	*P*-Value
Gear Type	NPV	No Environmental Risk No Insurance	<0.001
Insurance Level	NPV	Floating Bags High Environmental Risk	<0.001
Environmental Risk	NPV	Floating Bags No Insurance	<0.001

4.2. *Environmental risk*

Changes in the likelihood of adverse environmental events occurring had a predictable association with profit and cash position. Across all gear types with no insurance, as environmental risk increased, profit and annual cash positions decreased. Variance in cash position also increased, as seen in Fig. 4. The Kruskal Wallis test rejected the null hypothesis that the distributions of NPVs for floating bags at the three levels of environmental risk were the same at a 99% confidence level, Table 4.

While the floating bag system was negatively affected by environmental risk, it still had a positive average cash position by year 10 in the high-risk scenario. Floating cages had zero instances of a positive cash position by year 10 in either the Cedar Key or high-risk level scenarios. Adjustable longlines fared better with a positive average simulated cash position in the Cedar Key risk level scenario but turned negative in the high-risk level scenario. The comparison of the three equipment types in the Cedar Key and high-risk level scenarios can be seen in Fig. 5 and Fig. 6, respectively.

4.3. *Insurance coverage*

When the four insurance levels were compared with the Kruskal

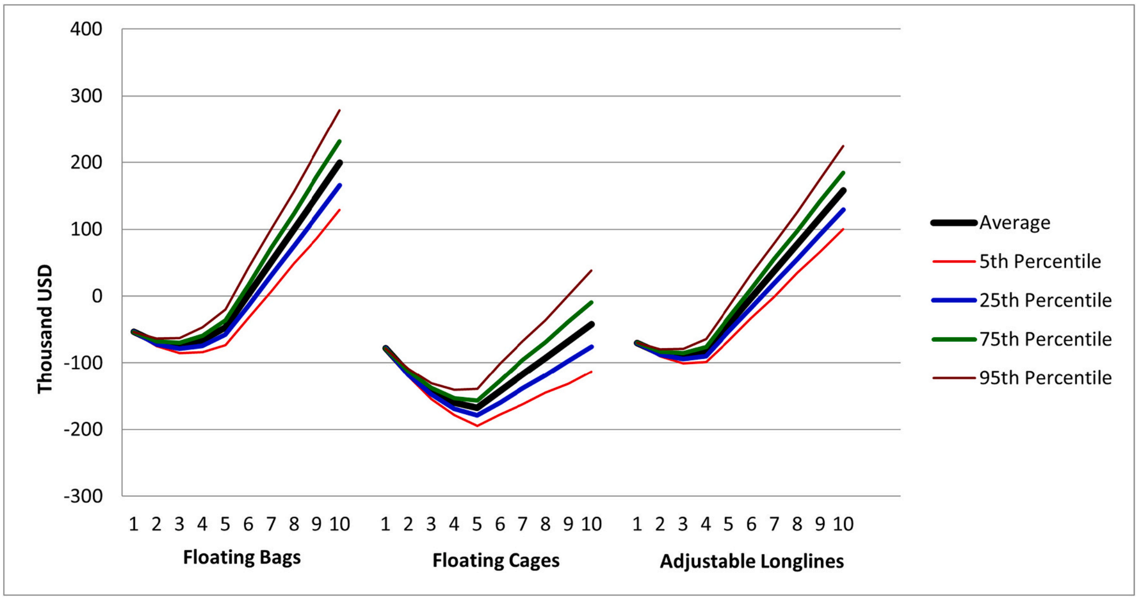

Fig. 3. Ten-year simulation of annual cash positions, across gear types, with no environmental risk or insurance.

Wallis test, they were statistically different at a 99% confidence level. However, upon closer analysis, the economic difference between the four insurance options was small, as seen in Fig. 7. No insurance level had first order stochastic dominance. Overall, the base level insurance had the highest average NPV, closely followed by non-insured. It is up to the discretion of each firm whether they wish to purchase insurance as it has a relatively small net impact on average. This may be due to the accurate pricing of NAP insurance as well as the relative infrequency of insurance payouts. In scenarios of high environmental risk and the lowest insurance trigger, the maximum likelihood of receiving an insurance payout was about 3%. Most scenarios had a likelihood of insurance payouts closer to 0%.

Table 5
Sensitivity analysis of selected variables on steady state profit for floating bags.

	Percent Change						
Variable	-25%	−15%	−5%	0%	5%	15%	25%
Y5 Oyster planted	−104%	−62%	−20%	0%	22%	64%	101%
Survival rate	−134%	−87%	−29%	0%	31%	105%	180%
Oyster seed price	6%	3%	0%	0%	2%	−5%	−12%
Labor hours	18%	13%	5%	0%	−2%	−11%	−22%
Wage unskilled	7%	2%	−1%	0%	−2%	−6%	−9%
Y5 Ve	33%	21%	1%	0%	−1%	−13%	−27%
Market Price	−105%	−63%	−21%	0%	19%	58%	98%

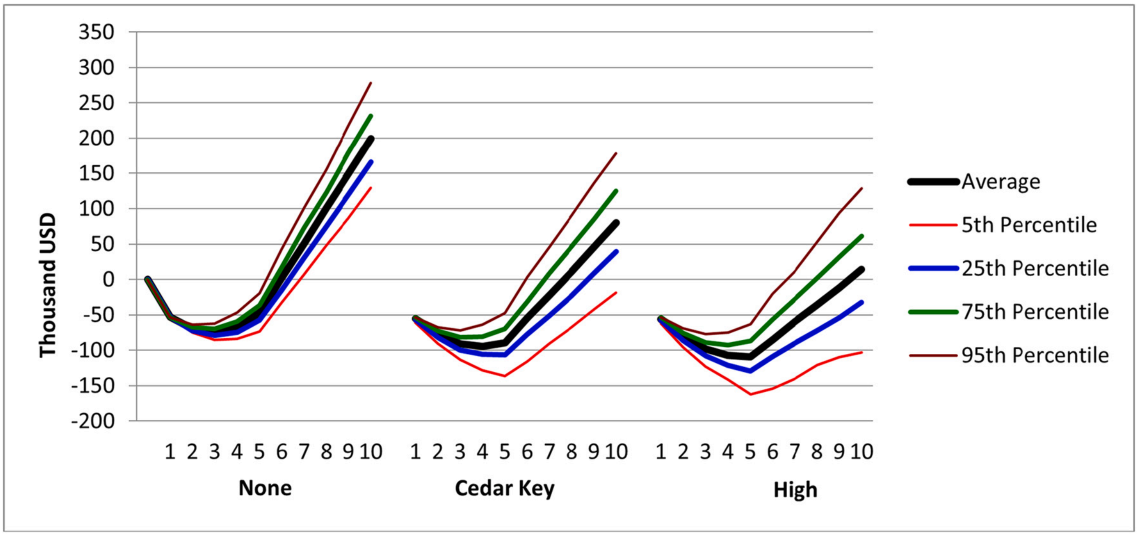

Fig. 4. Ten-year simulation of annual cash positions for non-insured floating bag systems, across environmental risk scenarios.

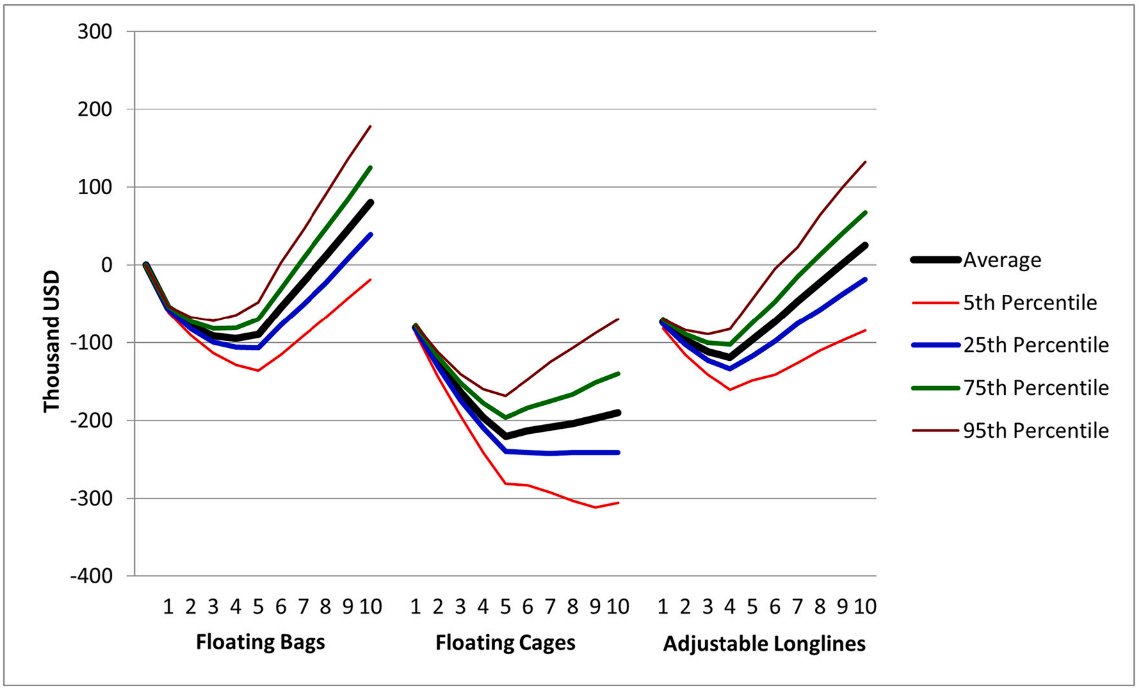

Fig. 5. Ten-year simulation of annual cash positions, across gear types, encountering environmental risks similar to Cedar Key when uninsured.

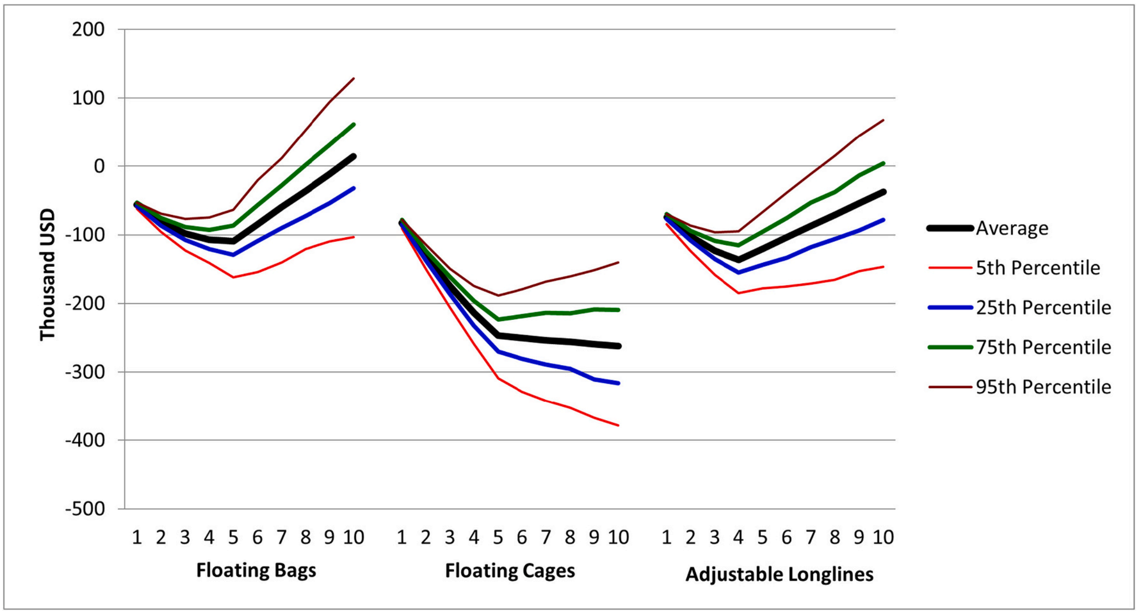

Fig. 6. Ten-year simulation of annual cash positions, across gear types, encountering high levels of environmental risks and uninsured.

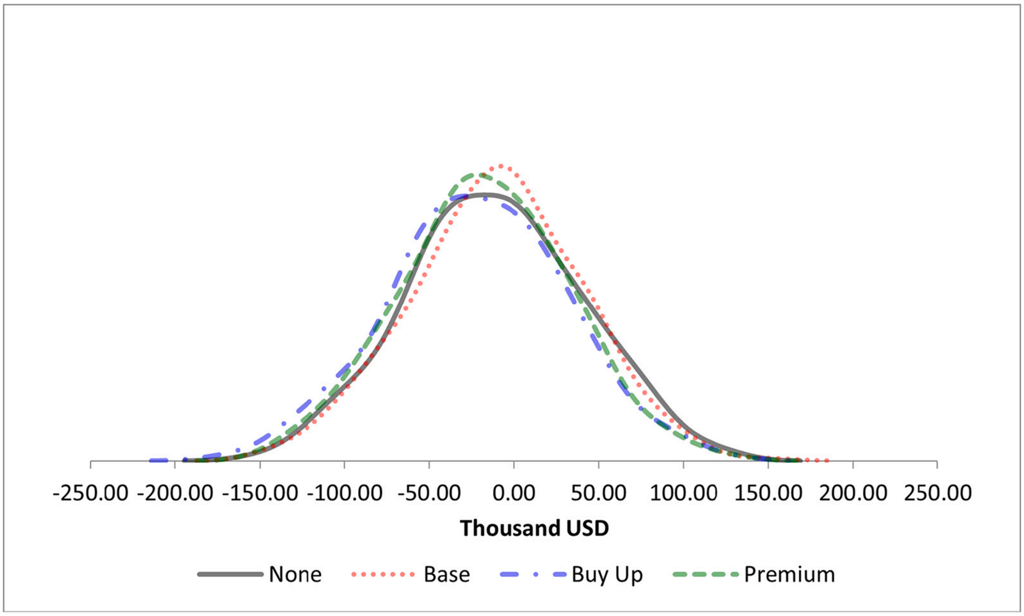

Fig. 7. PDF of NPV for floating bag systems according to insurance level when encountering high environmental risk levels.

4.4. *General results*

Our analysis indicates that the floating bag production system is both less costly to set up and more profitable than the other systems. Adjustable longlines also have substantial upside due to comparatively low required labor and lower long-term production cost as seen in Fig. 8. However, adjustable longlines have a considerable startup cost (Table 1). Another downside for adjustable longlines when compared to other gear systems is its low maximum production per acre. This problem could be partially rectified if a quad-run setup was used instead of the dual-run system. Systems that allow for more dense production, such as cross-line variants or the quad-run setups, merit further investigation. It would also be of interest to see the effects increasing plot size above 1.5 acres. It is possible that economies of scale could make all three equipment systems more profitable and less susceptible to bankruptcy.

Future simulations of GOM oyster profitability would benefit from a better understanding of labor requirements and research directly comparing the differences in gear systems and how they are affected by the stochastic risks. Specific gaps in the literature include differences in equipment hardiness in the event of storms and whether oysters grown in a particular system could garner different market prices. Further research on the covariance of effects of simultaneous stressors, and the rise of Spring/Summer mortality events (Wadsworth et al., 2019) would also be of value as the cause of these events is not fully understood, and therefore we do not know if they would be eligible for coverage by NAP.

5. Conclusions and discussion

Mollusks are an aquaculture product that are grown in locations across the globe and is the second most important species category in U.

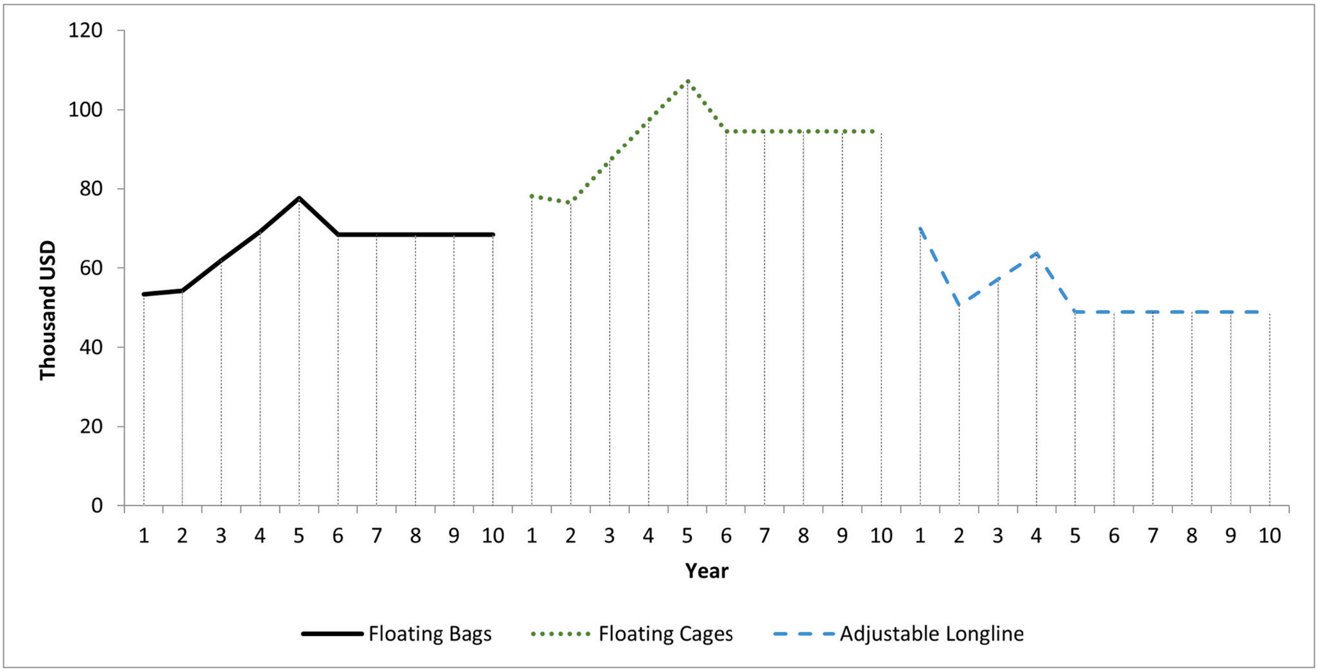

Fig. 8. Total annual cost of production across equipment systems when there is no environmental risk or insurance costs.

S. aquaculture. This is partially due to the relatively few manual inputs required and a variety of production techniques that make mollusk farming flexible to a firm's budget or access to technology. However, compared to other aquaculture products (finfish and crustaceans) and production systems (pond-based and recirculating aquaculture systems) environmental risks impact production to a much greater extent. As shown in our Gulf of Mexico example, differences in local environmental characteristics and production systems used can greatly influence profitability. This is similar to traditional agriculture, where different crops or strains will thrive in varying conditions. Unlike traditional agriculture, there is little research on the financial viability and risks associated with mollusk production. This paper provides a framework for future shellfish risk research to be applied to other regions and species with unique environmental and production characteristics.

When applying the model, we must be cognizant of the unique challenges to each region being analyzed and the species being farmed. For example, shellfish grown in the northeastern United States face a longer grow out compared to the GOM and greater potential temporal exposure to disease. Therefore, a disease specific variable would be valuable in modeling production risk in the northeastern United States. This additional risk would also inform other types of risk mitigation strategies to evaluate such as, paying a premium for a disease resistant shellfish variety, or varying stocking densities. Other risk variables that should be considered are 1) water quality, which could vary according to pollution or a naturally occurring event like harmful algal blooms 2) ocean acidification, which affects both the Atlantic and Pacific coastlines, and 3) predation, a common problem for on-bottom production systems. The risks and mitigation strategies included in the model should be relevant to the region and species in question.

Author statement

Details of each author with their contribution in this paper:

Name of the author and e-mail ID	Types of contribution
Jordan Moor, jordanmoor@ufl.edu	Developed the idea, collected data, conducted analysis and wrote paper
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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Enterprise budget in Year 6 for 1.5 acres and no stochastic risk.

Item	Floating Bags			Floating Cages			Adjustable Long Lines		
	Quantity	Price	Value or Cost	Quantity	Price	Value or Cost	Quantity	Price	Value or Cost
Gross Receipts (Oysters)	257,400	$ 0.45	$ 115,830.00	262,080	$ 0.45	$ 117,936.00	194,643	$ 0.45	$ 87,589.35

(*continued on next page*)

Table A1 (*continued*)

Item	Floating Bags			Floating Cages			Adjustable Long Lines		
	Quantity	Price	Value or Cost	Quantity	Price	Value or Cost	Quantity	Price	Value or Cost
Variable Costs									
Oyster Seed	325,000	$ 0.03	$ 8125.00	320,000	$ 0.03	$ 8000.00	267,000	$ 0.03	$ 6675.00
24″ zip ties	5852	$ 0.25	$ 1463.00						
8″ zip ties	8948	$ 0.04	$ 357.92						
ID tags	2237	$ 0.25	$ 559.25	2202	$ 0.25	$ 550.50	2664	$ 0.25	$ 666.00
Owner/operator	2080	$ 13.00	$ 27,040.00	2080	$ 13.00	$ 27,040.00	2080	$ 13.00	$ 27,040.00
Hired Labor	1092	$ 9.00	$ 9828.00	2184	$ 9.00	$ 19,656.00		$ 9.00	
Crop Insurance (Base Level)			$ 325.00			$ 325.00			$ 325.00
Repair and Maintenance			$ 716.74			$ 968.89			$ 934.22
Fuel			$ 2663.00			$ 2663.00			$ 2663.00
Total Variable Costs			$ 51,077.91			$ 59,203.39			$ 38,303.22
Income Above Variable Costs			$ 64,752.09			$ 58,732.61			$ 49,286.13
Fixed Costs									
Bookkeeping			$ 700.00			$ 700.00			$ 700.00
Depreciation			$ 14,642.61			$ 14,670.03			$ 12,307.28
Boat Insurance			$ 600.00			$ 600.00			$ 600.00
Lease & Certification Fees			$ 165.19			$ 165.19			$ 165.19
Interest Expense			$ 1500.00			$ 1500.00			$ 1500.00
Total Fixed Costs (Before Taxes)			$ 17,607.80			$ 17,635.22			$ 15,272.47
Total Costs (Before Taxes)			$ 68,685.72			$ 76,838.61			$ 53,575.69
Earnings Before Taxes			$ 47,144.28			$ 41,097.39			$ 34,013.66
Breakeven Price									
To Cover Variable Costs			$ 0.20			$ 0.23			$ 0.20
To Cover Total Costs			$ 0.27			$ 0.29			$ 0.28

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