Management Evaluation for the Chesapeake Bay Blue Crab Fishery: An Integrated Bioeconomic Approach

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Abstract

An integrated bioeconomic model is built based on an individual-based simulation model and a stock assessment model for the Chesapeake Bay blue crab fishery. The resulting model is able to not only compare alternative management scenarios being considered by policy makers in terms of both sustainable yield (SY) and sustainable revenue (SR), but also provide insights into impacts of relevant policy factors that together form management scenarios. The preliminary regression results based on simulated management scenarios show variations in effects of different policy factors, suggesting that the fishery policies should be made accordingly.

1. Introduction

Fishery management policies based on biological reference points intend to keep stable development for the fishery while maintaining sustainable outcomes. Fisheries policy makers usually implement a set of policy factors that help achieve specific goals such as maximum sustainable yield (MSY), maximum sustainable revenue (MSR), or a threshold for spawning biomass of the stock. When fisheries managers make their decisions, they often want to obtain information of possible outcomes before the fisheries policies are implemented.

For real fisheries problems, different management strategies may lead to varying consequences. Furthermore, the power of each potential policy factor is of interest to policy makers. Here, we develop a framework to explore the potential effects of management scenarios that are composed with many policy factors on fisheries from both the biological and economic perspectives, and further identify the impact of each policy factor on sustainable outcomes in a management scenario.

For management evaluation, simulation is a useful tool that can demonstrate the potential outcomes of specific management policies. It is widely used for many fisheries (Bastardie, Nielsen, & Kraus, 2010; Bunnell & Miller, 2005; Bunnell, Lipton, & Miller, 2010; Helser, Thunberg, & Mayo, 1996; Kell & Bromley, 2004; Kraak et al., 2008; Needle, 2008; Pastoors, Poos, Kraak, & Machiels, 2007). The simulation procedure can not only assess relative performance of different management policies, but also determine expected performance to specified management strategies (Butterworth & Punt, 1999). On the other hand, a comprehensive stock assessment for a fishery is another tool, which provides a solid foundation for making policy decisions such as MSY-based reference points (A'mar, Punt, & Dorn, 2010; Ives, Scandol, & Greenville, 2013; Maravelias, Hillary, Haralabous, & Tsitsika, 2010). This type of model is usually based on real stock survey data.

The framework presented in our paper combines the two major modeling approaches for fisheries management to form an integrated operating model. The policy factors for regulations serve as inputs to the resulting model. These factors on the purpose of preserving fish stocks together constitute a management scenario (Ives et al., 2013; Kraak et al., 2008; Pastoors et al., 2007), which is later evaluated based on selected performance criteria, such as spawning biomass or sustainable outcomes (A'mar, Punt, & Dorn, 2008; Dichmont et al., 2008; Ives et al., 2013). The performance measures in our model include both biological and economic criteria, since the commonly used biological MSY-based criterion alone may not provide a comprehensive objective due to complexities of fisheries systems (Pilling et al., 2008).

In this study, the bioeconomic model is based on two current models for the Chesapeake Bay blue crab fishery (Bunnell et al., 2010; Miller et al., 2011). The blue crab is an iconic species in Chesapeake Bay and greater Mid-Atlantic Region. Blue crab is not only a crucial component of the Chesapeake Bay ecosystem, but also the largest source of crabs in U.S., accounting for 50% of the total blue crab harvest (Miller et al., 2011). Economically, blue crab is one of the most profitable commercial fisheries in Chesapeake Bay (Miller et al., 2011), ranging from $46-103 million annually (Bunnell et al., 2010). It is therefore important to examine effects of different fishery policies on the fishery itself, and consequently the performance associated with management scenarios.

2. Methods

The integrated operating model

The operating model is integrated with two models regarding blue crab in Chesapeake Bay. The first model is a stock assessment model developed by (Miller et al., 2011), in which a set of stock-recruitment parameters is estimated. Given specific fishing mortality rates and estimated stock-recruitment parameters, SY can be identified based on the stock-recruitment model (Shepherd, 1982). Thus, the fishing mortality rate that maximizes the sustainable yield can be determined.

However, there are no policy and economic implications in the stock assessment model. To add these two components into the fishery management, an individual-based model developed by (Bunnell & Miller, 2005; Bunnell et al., 2010) is employed. The model is a sex-specific, per-recruit bioeconomic model that simulates growth, maturity and mortality of all individuals over two years and predicts prices on a daily basis. In this model, the inputs are fishing policies, while the outputs include various biological and economic components, such as proportion of each market category harvest and daily price predictions, etc.

The modeling strategy in this study is to build an integrated model in a fashion that the resulting model combines the main features of both the stock assessment model and the individual-based model. For example, the stock assessment model provides comprehensive biological estimates such as sustainable yield and equilibrium exploitation rate, but it lacks of economic and policy implications. The individual-based model can examine specific economic outcomes of the blue crab fishery regulated by different fishery policies, but there are no sustainable outcomes based on realistic stock survey data. The integrated operating model can evaluate various management scenarios from the sustainable standpoint. Figure 1 outlines the key components and paths of building the operating model.

1. In a single management scenario case composed with many predetermined policies, the individual-based model simulates the fate of all individual crabs. At the end of each simulation, we can obtain how many age-specific and sex-specific blue crabs are harvested under this management scenario. According to the realized outcomes, we estimate fishing mortality rates for both sexes and ages using the Baranov’s catch equation (Bunnell & Miller, 2005; Quinn II & Deriso, 1999). The equation is presented in the Appendix.

2. Given the separately estimated stock-recruitment parameters from the stock assessment model and the realized fishing mortality rates from the individual-based model, we estimate the sustainable yield associated with this management scenario by a set of equations (Miller et al., 2011; Shepherd, 1982). The steps of calculating the sustainable yield and associated exploitation rate are also presented in the Appendix.

3. To add economic implications, we use the demand estimation and the proportion of harvest for each market category from the individual-based model. We first decompose the annual total sustainable harvest calculated from the second step into four different market categories on a daily basis according to the proportion results obtained from the individual-based model. The daily prices for all market categories are predicted based on the estimated inverse demand functions given the number of sustainable harvest.

The previous three steps can be applied to each management scenario. Policy makers might also be interested in which policy factors to what extent affect the sustainable outcomes. The knowledge of the impact of each policy factor is important because these are the major tools for policy makers to regulate the fishery. We introduce the Monte Carlo integration method into the model such that each policy factor is allowed to randomly select a value from a reasonable range for one simulated scenario. We can simulate many scenarios with this strategy. The sustainable outcomes associated with each simulated scenario are estimated by the previous three steps.

Performance measures

The performance measures for management scenarios are chosen to evaluate objectives in terms of blue crab conservation and economic returns. The measures are outputs from the operating model given a specified management scenario. The first measure is SY. It is selected because it assesses biological outcomes of different fishery policies that provide information for the status of the blue crab stock. The second criterion is SR, which includes economic implications. The SR is chosen because it measures the ability of management scenarios to achieve socio-economic outcomes while maintaining yield at sustainable levels.

3. Results and Discussion

Performance of current and alternative management scenarios

We first evaluate the performance of management scenarios considered in (Bunnell et al., 2010). Descriptions of all 15 regulations are presented in Table 2 in the Appendix, which is adapted from their paper. Among these scenarios, there are six that were implemented by Maryland and Virginia regulatory agencies. The other nine scenarios are proposed by the authors by varying certain policy factors.

For the Chesapeake Bay blue crab fishery, management scenarios mainly differ with respect to the length of the fishing season or the minimum and maximum harvestable size limit for different market categories (Bunnell et al., 2010; Miller et al., 2011). SY and SR for 15 management scenarios in (Bunnell et al., 2010) are estimated in our integrated operating model. The sustainable results are graphed in Figure 2. It shows that these scenarios generate varying SY and SR.

There are three management scenarios, “2008MDRegs”, “2009MDRegs” and “10.1-12.15_FEM”, that lead to both high SY and SR. These three have more restrictions on female fishing season in terms of early end date or intermittent fishing closures, implying that regulating female fishing activity is a good policy tool for the Chesapeake Bay blue crab fishery.

Two regulations used by Virginia, “2007VARegs” and “2009VARegs”, generate medium SY but relatively low SR. In these two scenarios, the minimum size limit for males and immature females remains the same during a fishing season. These results imply that upgrading the minimum size limit for males and immature females during a fishing season can increase SR for the blue crab fishery.

Three scenarios, “165_MaxFemCW”, “152_MaxFemCW” and “152_MinFemCW”, show completely different patterns with much higher sustainable yield but lower sustainable revenue compared to others. These three scenarios include size limits imposed on mature females. The results may attribute to the large amount of yield driving down the predicted prices for certain market categories according to the estimated demand system from the individual-based model.

Effects of policy factors

In order to examine the effect of each policy factor on both biological and economic performance, we simulate 4,000 hypothetical management scenarios using the Monte Carlo integration method. For instance, we set the male fishing start-date within the range between March 15 and April 1, in which the start-date randomly selects a value for one management scenario. Other policy factors are determined in the same manner. It should be noted that although policy factors are randomly selected in our model, it does not mean that the management scenarios should be randomly determined. We adopt this method because we want variations in variables to examine the effects of policy factors.

The combinations of SY and SR for all simulated scenarios are also illustrated in Figure 2 along with the scenarios in (Bunnell et al., 2010). These scenarios generate quite different sustainable outcomes, as shown with blue dots.

We first cluster the scenarios based on mature female size limit policy with different colors, as shown in Figure 3. It indicates that this policy is the driving force that separates the simulated scenarios. The scenarios with minimum size limit for mature females, i.e., sizes of harvestable crabs must be greater than the limit, lead to lower level of SY, as shown with green dots. The scenarios with maximum size limit, i.e., sizes of harvestable crabs must be less than the limit, result in higher SR, as shown with red dots.

To quantify the impact of each policy factor, we regress SR and SY on all policy factors in our model, respectively. The estimated coefficients can be interpreted as the effect of one unit change of policy factors on sustainable outcomes. In Chesapeake Bay, there are many policy tools that are already used or can be used to regulate the blue crab fishery. The regression results are shown in Table 1. A variety of insights can be inferred from the results.

Male fishing season

Regulations on fishing season length are widely used for the blue crab fishery in Chesapeake Bay. The fishing activity is prohibited during the winter season. Usually, the fishing season starts around April 1, and ends until December 15. In our model, we make male and female fishing season start-date and end-date as fishing season variables.

The coefficients associated with male fishing season in Table 1 indicate that postponing start-date and end-date by one day can increase SR, as shown by 0.1342 and

0.2173, respectively. However, starting male fishing season one day later will decrease SY (-0.3345), while ending the season one day later will increase SY (1.4010). These results imply that longer male fishing season results in higher SY, and later male fishing season is more favorable in terms of higher SR.

Female fishing season

The policy associated with female fishing season is different for the Chesapeake Bay blue crab fishery. Not only the female fishing is prohibited in winter, but also it is allowed to close intermittently during a season. This type of policy is implemented by Maryland regulators in 2009. Among our simulated scenarios, we allow female fishing season close once or twice.

First, the estimated coefficients associated with female start-date and end-date in Table 1 indicates that starting female season one day later increases the SR by 0.0580 million dollars for the fishery, while ending it one day later decreases the SR by 0.0896 million. For SY, the results are similar. These results imply that shorter female fishing season results in both higher SR and SY. It is likely due to shorter female fishing season being able to preserves the female stock that is important for breeding.

Second, coefficients corresponding to female fishing season closure dummies are significantly positive except for one. This implies that intermittent season closure is a favorable policy for the Chesapeake Bay blue crab fishery. In addition, the effect of the number of closure days is also examined. The coefficient associated with SY is significantly positive (0.1289), which indicates that closing female fishing for one more day during a season can result in 0.1289 million more sustainable yield.

Male and immature female minimum size limit

Minimum size limit for males and immature females has been implemented for the Chesapeake Bay blue crab fishery. This policy intends to protect juvenile crabs. Usually, the size limits are the same for both males and immature females. In our model, we follow this rule. For some management scenarios, the minimum size limit is allowed to change after a certain date during the fishing season. For example, regulatory agency in Maryland sets the minimum size limit at 127 mm through July 15 since fishing season starts, and 133 mm thereafter. However, in Virginia, the minimum size limit remains the same throughout the fishing season. In our model, the minimum size limit first randomly selects a number since the fishing season starts. Then, after a randomly determined date, the minimum size limit either remains the same, or randomly upgrade to a higher level.

The coefficient associated with initial minimum size limit is significantly positive for SR (0.6313), but negative for SY (-1.4833). It indicates that increasing the minimum size limit by 1 mm at the beginning of a fishing season, i.e., making the policy more restrictive, can generate 0.6313 million more SR, but reduce 1.4833 million SY. Upgrading the minimum size limit in the middle of a season appears to bring about similar effect on SR (0.5409) and SY (-1.2326).

Peeler minimum size limit

Similar to males and immature females, there is minimum size restriction for peelers. The 2007 Maryland regulations include the 82.5 mm size limit for peelers before July 15, and 89 mm thereafter (Bunnell et al., 2010). In our model, a management scenario first randomly selects a minimum size limit for peelers. After a certain day, the scenario will also be decided to either upgrade the limit or not. If so, the new size limit will be randomly selected. The regression results associated with this policy are similar to the male and immature female size limit, but with different magnitudes.

Soft-shell crabs minimum size limitation

Minimum size limit is implemented for soft-shell crabs in Chesapeake Bay. This limit is usually set constant over a fishing season. In 2007 Maryland regulations, for example, the minimum size limit for soft-shell crabs is 89 mm for the entire season (Bunnell et al., 2010). In our model, we make all simulated scenarios include soft-shell minimum size limit, which is also randomly selected. The estimated coefficient for SR and SY are both significantly negative, suggesting that this policy is of little benefit to the blue crab fishery.

Mature female size limits

In real management scenarios, there is no size restriction for mature females. To examine the potential effect of this policy, simulated scenarios either include maximum or minimum size limit for mature females. The proposed policy is used to protect female crabs that are crucial for stock recruitment.

In our model, there are three different scenarios in terms of mature female size limit. A simulated management scenario is determined to impose maximum size limit, minimum size limit, or no size limit for mature female crabs. The estimated coefficients are all significantly negative for the two size limit variables, but they have different implications. The larger the minimum size limit, the more restrictive the policy is. However, the larger the maximum size limit, the less restrictive the policy is.

The use of less restrictive maximum size limit, i.e., increasing the limit, will lead to lower SR (-0.3214) and SY (-0.7989). This implies that more restrictive maximum size limit protects more adult females from being harvested. Contrary to maximum size limit, more restrictive minimum limit, i.e., increasing the limit, can generate both lower SR (-0.4399) and SY (-2.5812), suggesting that the minimum size limit should be set at a low level. It should be noted that the magnitude for the coefficient associated with minimum size limit in the SY equation is much bigger than others in absolute value (-2.5812). It indicates that increasing minimum size limit will substantially reduce SY, which is also shown in Figure 3.

4. Conclusions

The integrated bioeconomic model introduced in the paper is able to examine various management scenarios for an important fishery in Chesapeake Bay from the sustainable perspective. The modeling strategy by connecting a simulation model and a stock assessment model also provides insights for other fisheries modelers and managers. A simulation model provides a framework for generating potential outcomes of alternative management scenarios. A stock assessment model, on the other hand, provides a solid foundation for measuring performance. The resulting model not only can assist policy makers on evaluating considered management scenarios, but also provide information on effects of different policy factors that are relevant to their decisions.

The model estimates sustainable outcomes for 15 scenarios in (Bunnell et al., 2010) and 4,000 simulated scenarios. Then, we built a regression model to study the impacts of policy factors on both SR and SY. Some key findings can be gained from the regression results. Female fishing season should be shortened and intermittently closed to protect breeding females. More restrictive minimum size limit for males, immature females, and peelers can generate higher SR, but lower SY. For soft-shell crabs, the minimum size limit is not favorable, since they are the most valuable crabs in the blue crab market. Maximum size limit for mature females is a better policy than minimum size limit for mature females.

Although the model presents interesting results, it still can be improved in some ways. Firstly, the SR is estimated by using the demand estimation in the individual-based model, which is an inverse demand system with constant slopes. We can improve it by estimating a system-wide demand model for blue crabs. Secondly, to provide more meaningful information from the economic standpoint, cost estimation should be developed, and incorporated into the bioeconomic model to generate sustainable net revenue.

References

A'mar, Z. T., Punt, A. E., & Dorn, M. W. (2008). The management strategy evaluation approach and the fishery for walleye pollock in the gulf of alaska. Paper presented at the *Proceedings of 24th Lowell Wakefield Fisheries Symposium: Resiliency of Gadid Stocks to Fishing and Climate Change,* 317-346.

A'mar, Z. T., Punt, A. E., & Dorn, M. W. (2010). Incorporating ecosystem forcing through predation into a management strategy evaluation for the gulf of alaska walleye pollock (theragra chalcogramma) fishery. *Fisheries Research, 102*(1), 98-114.

Bastardie, F., Nielsen, J. R., & Kraus, G. (2010). The eastern baltic cod fishery: A fleet-based management strategy evaluation framework to assess the cod recovery plan of 2008. *ICES Journal of Marine Science: Journal Du Conseil, 67*(1), 71-86.

Bunnell, D. B., Lipton, D. W., & Miller, T. J. (2010). The bioeconomic impact of different management regulations on the chesapeake bay blue crab fishery. *North American Journal of Fisheries Management, 30*(6), 1505-1521.

Bunnell, D. B., & Miller, T. J. (2005). An individual-based modeling approach to spawning-potential per-recruit models: An application to blue crab (callinectes sapidus) in chesapeake bay. *Canadian Journal of Fisheries and Aquatic Sciences, 62*(11), 2560-2572.

Butterworth, D., & Punt, A. (1999). Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science: Journal Du Conseil, 56*(6), 985-998.

Dichmont, C., Deng, A., Punt, A., Ellis, N., Venables, W., Kompas, T., . . . Bishop, J. (2008). Beyond biological performance measures in management strategy evaluation: Bringing in economics and the effects of trawling on the benthos. *Fisheries Research, 94*(3), 238-250.

Helser, T. E., Thunberg, E. M., & Mayo, R. K. (1996). An age-structured bioeconomic simulation of US silver hake fisheries. *North American Journal of Fisheries Management, 16*(4), 783-794.

Ives, M., Scandol, J., & Greenville, J. (2013). A bio-economic management strategy evaluation for a multi-species, multi-fleet fishery facing a world of uncertainty. *Ecological Modelling, 256*, 69-84.

Kell, L., & Bromley, P. (2004). Implications for current management advice for north sea plaice (pleuronectes platessa): Part II. increased biological realism in recruitment, growth, density-dependent sexual maturation and the impact of sexual dimorphism and fishery discards. *Journal of Sea Research, 51*(3), 301-312.

Kraak, S., Buisman, F., Dickey-Collas, M., Poos, J., Pastoors, M., Smit, J., . . . Daan, N. (2008). The effect of management choices on the sustainability and economic performance of a mixed fishery: A simulation study. *ICES Journal of Marine Science: Journal Du Conseil, 65*(4), 697-712.

Maravelias, C. D., Hillary, R., Haralabous, J., & Tsitsika, E. V. (2010). Stochastic bioeconomic modelling of alternative management measures for anchovy in the mediterranean sea. *ICES Journal of Marine Science: Journal Du Conseil, 67*(6), 1291-1300.

Miller, T. J., Wilberg, M. J., Colton, A. R., Davis, G. R., Sharov, A., Lipcius, R. M., . . . Kaufman, A. G. (2011). *Stock assessment of blue crab in chesapeake bay 2011.* (). Norfolk, VA: NOAA Chesapeake Bay Office.

Needle, C. L. (2008). Management strategy evaluation for north sea haddock. *Fisheries Research, 94*(2), 141-150.

Pastoors, M. A., Poos, J. J., Kraak, S. B., & Machiels, M. A. (2007). Validating management simulation models and implications for communicating results to stakeholders. *ICES Journal of Marine Science: Journal Du Conseil, 64*(4), 818-824.

Pilling, G. M., Kell, L. T., Hutton, T., Bromley, P. J., Tidd, A. N., & Bolle, L. J. (2008). Can economic and biological management objectives be achieved by the use of MSY-based reference points? A north sea plaice (pleuronectes platessa) and sole (solea solea) case study. *ICES Journal of Marine Science: Journal Du Conseil, 65*(6), 1069-1080.

Quinn II, T. J., & Deriso, R. B. (1999). *Quantitative fish dynamics*. New York, USA: Oxford University Press.

Shepherd, J. (1982). A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. *Journal Du Conseil, 40*(1), 67-75.

Table 1: Regression results from the simulated management scenarios

Policy Factors	Sustainable Revenue (Million Dollars)	Sustainable Yield (Million Crabs)
Start-Date – M (day)	0.1342***	-0.3345***
	(0.0047)	(0.0188)
End-Date – M (day)	0.2173***	1.4010***
	(0.0019)	(0.0077)
Start-Date – F (day)	0.0580***	0.1746***
	(0.0047)	(0.0190)
End-Date – F (day)	-0.0896***	-0.2574***
	(0.0029)	(0.0116)
1 Season Closure – F (0 or 1)	0.3255	6.2202***
	(0.2760)	(1.1046)
2 Season Closures – F (0 or 1)	2.9901***	4.7589***
	(0.2671)	(1.0689)
Closure Days – F (day)	-0.0094	0.1289***
	(0.0063)	(0.0251)
Initial Min Size Lim – M & F_0 (mm)	0.6313***	-1.4833***
	(0.0177)	(0.0710)
Δ Min Size Lim – M & F_0 (mm)	0.5409***	-1.2326***
	(0.0174)	(0.0697)
Δ Min Size Lim – M & F_0 (0 or 1)	0.1296	-0.4483
	(0.1999)	(0.8000)
Initial Min Size Lim – P (mm)	0.0140	-0.6654***
	(0.0188)	(0.0752)
Δ Min Size Lim – P (mm)	0.0713***	-0.5159***
	(0.0169)	(0.0676)
Δ Min Size Lim – P (0 or 1)	0.4470**	-0.7371
	(0.1938)	(0.7756)
Min Size Lim – S (mm)	-0.0649***	-0.2345***
	(0.0098)	(0.0390)
Max Size Lim – F_1 (mm)	-0.3214***	-0.7989***
	(0.0147)	(0.0587)
Min Size Lim – F_1 (mm)	-0.4399***	-2.5812***
	(0.0147)	(0.0590)
Constant	26.0905***	413.9690***
	(4.1742)	(16.7070)

The contents in the parenthesis associated with policy factors are units for the explanatory variables.
*** $p<0.01$, ** $p<0.05$

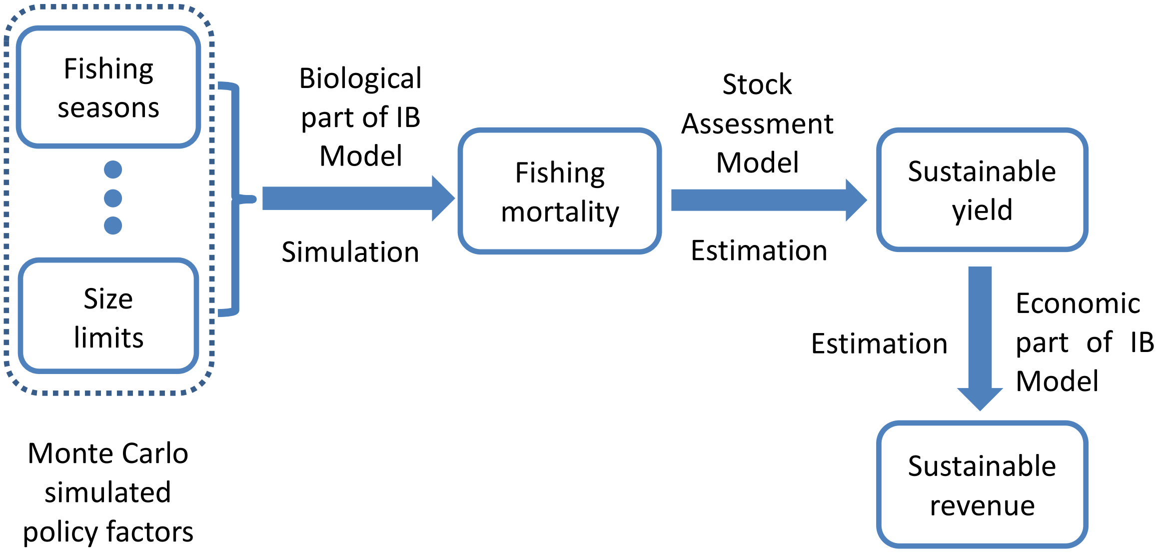

Figure 1: Flowchart depicting the key components and paths of the integrated bioeconomic model

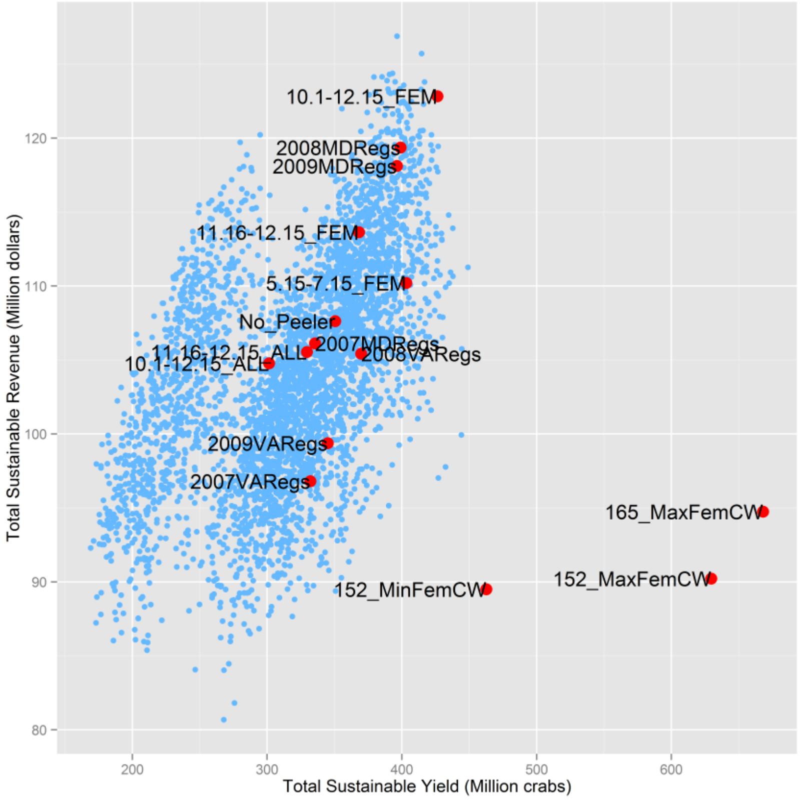

Figure 2: Sustainable yield and sustainable revenue for 15 management scenarios (red dots) in (Bunnell et al., 2010) and 4,000 simulated management scenarios (blue dots)

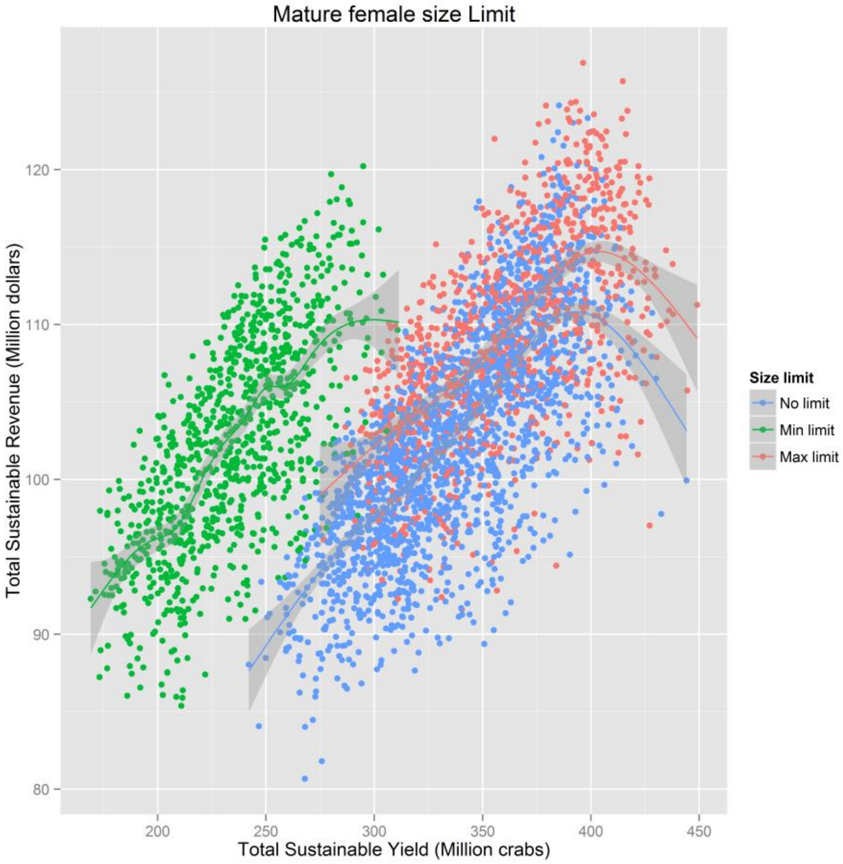

Figure 3: Clustered simulated scenarios based on mature female size limit

Appendix

Steps of calculating sustainable yield and sustainable revenue

Step 1: calculate realized fishing mortality associated with one management scenario.

The realized fishing mortality associated with a management scenario is calculated by the Baranov's catch equation (Bunnell & Miller, 2005; Quinn II & Deriso, 1999). Since the individual-based model simulates sex-specific harvest over two-year periods, we can calculate sex-specific and age-specific fishing mortality rate, given the predetermined initial recruitment at the beginning of a simulation. The formula is specified as:

$$F_{st} = \frac{C_{st} Z_{st}}{N_{st}^{0}\left(1 - e^{-2Z_{st}}\right)},$$

where C_{st} equals the total number of crabs harvested for $s \in \{male, female\}$ and $t \in \{0,1\}$, and N_{st}^{0} represents the simulated number of sex-specific blue crabs alive at the beginning of fishing season year t. Z_{st} equals the age-specific and sex-specific total mortality rate, which is calculated as:

$$Z_{st} = \frac{\ln\left(N_{st}^{0}\right) - \ln\left(N_{st}^{T}\right)}{2},$$

where N_{st}^{T} represents the simulated number of blue crabs alive at the end of year t.

Step 2: Calculate the corresponding annual total sustainable yield.

The method of calculating sustainable yield follows the stock-recruitment model given estimated stock-recruitment parameters from the stock assessment model (Miller et al., 2011; Shepherd, 1982). The sex-specific and age-specific fishing mortality rates calculated from Step 1 are used in this step. The sustainable yield is calculated with the following steps for each management scenario, which is mainly adapted from (Miller et al., 2011).

1. Spawners per recruit (SPR) for each sex is calculated, which is the function of sex-specific fishing mortality rate and natural mortality rate:

$$SPR_s = \frac{x_s e^{-((1+\kappa)M + F_{s0} + \kappa F_{s1})}}{1 - e^{-(M + F_{s1})}},$$

where x_s equals to 0.52 denoting the sex ratio at recruitment; κ is selected as 0.37 representing the proportion of mortality before spawning; M represents the natural mortality rate that is selected as 0.9 in the model; F_{s0} and F_{s1} are realized fishing mortality rate for age-0 and age-1 crabs, respectively.

2. Abundance associated with yield per recruit (YPR) and YPR are calculated by applying the Baranov catch equation, that is,

$$N_{YPR,s} = \frac{x_s e^{-(M + F_{s0})}}{1 - e^{-(M + F_{s1})}},$$

$$YPR_s = \frac{F_{s1}}{M + F_{s1}}\left(1 - e^{-(M + F_{s1})}\right) N_{YPR,s} + \frac{F_{s0}}{M + F_{s0}}\left(1 - e^{-(M + F_{s0})}\right) x_s$$

3. Based on sex-specific SPR, equilibrium abundance of age-1 is calculated by rearranging the Ricker stock-recruitment function,

$$N_{eq,s} = \frac{\ln SPR_f + \ln \alpha + \sigma_R^2 / 2}{\beta} \times \frac{SPR_s}{SPR_f + SPR_m},$$

where α, β, and σ_R^2 are estimated from the stock assessment model. We treat these three parameters as given in the process of calculating sustainable yield in our model.

4. Equilibrium recruitment is calculated, which is the function of equilibrium abundance and SPR calculated in previous steps:

$$R_{eq,s} = \frac{N_{eq,s}}{SPR_s}$$

5. Sex-specific sustainable yield and total sustainable yield are obtained:

$$C_{eq,s} = R_{eq,s} YPR_s,$$

$$C_{eq} = \sum_s C_{eq,s}$$

Step 3: Decompose the annual total sustainable yield into daily and category-specific sustainable yield.

The individual-based model simulates the number of harvest for each market category each day over two-year periods. The initial recruitment for each simulation is predetermined, which is not based on stock assessment. In this case, the result of total harvest from the individual-based model must be less than the initial recruitment. We use the proportion of each category harvest from the individual-based model instead of the absolute numbers of harvest. We decompose the total sustainable yield calculated from Step 2 into daily category-specific harvest, according to the proportion information obtained from the individual-based model.

Step 4: Calculate sustainable revenue

The daily sustainable harvest is the summation of harvest in the same day of first year (age-0 crabs) and second year (age-1 crabs) in the individual-based model. Then we apply the estimated inverse demand equations in the individual-based model to predicting daily prices for all market categories given the daily sustainable harvest estimated in Step 3. The daily sustainable revenue for each market category is the multiplication of daily sustainable harvest and predicted price. The total sustainable revenue for one management scenario is the summation of all daily sustainable revenue.

Table 2: Management scenarios being implemented by regulators or proposed by (Bunnell et al., 2010)

Scenario	Male fishing season	Female fishing season	Min size limit for males & immature females (mm)		Min size limit for peelers (mm)		Size limit for soft-shell crabs (mm)	Size limit for mature females (mm)	
			Before 7/15	After 7/15	Before 7/15	After 7/15		Min	Max
2007VARegs	17 Mar – 30 Nov	17 Mar – 30 Nov	>127	>127	>76	>76	>89	-	-
2008VARegs	17 Mar – 30 Nov	17 Mar – 26 Oct	>127	>127	>82.5	>89	>89	-	-
2009VARegs	17 Mar – 30 Nov	17 Mar – 20 Nov	>127	>127	>82.5	>89	>89	-	-
2007MDRegs	1 Apr – 15 Dec	1 Apr – 15 Dec	>127	>133	>82.5	>89	>89	-	-
2008MDRegs	1 Apr – 15 Dec	1 Apr – 23 Oct	>127	>133	>82.5	>89	>89	-	-
2009MDRegs	1 Apr – 15 Dec	1 Apr – 31 May, 16 Jun – 25 Sep, 5 Oct – 10 Nov	>127	>133	>82.5	>89	>89	-	-
5/15-7/15_FEM	1 Apr – 15 Dec	1 Apr – 14 May, 16 Jul – 15 Dec	>127	>133	>82.5	>89	>89	-	-
10/1-12/15_FEM	1 Apr – 15 Dec	1 Apr – 30 Sep	>127	>133	>82.5	>89	>89	-	-
11/16-12/15_FEM	1 Apr – 15 Dec	1 Apr – 15 Nov	>127	>133	>82.5	>89	>89	-	-
10/1-12/15_ALL	1 Apr – 30 Sep	1Apr – 30 Sep	>127	>133	>82.5	>89	>89	-	-
11/16-12/15_ALL	1 Apr – 15 Nov	1 Apr – 15 Nov	>127	>133	>82.5	>89	>89	-	-
152_MinFemCw	1 Apr – 15 Dec	1 Apr – 15 Dec	>127	>133	>82.5	>89	>89	>152	-
152_MaxFemCW	1 Apr – 15 Dec	1 Apr – 15 Dec	>127	>133	>82.5	>89	>89	-	<152
165_MaxFemCW	1 Apr – 15 Dec	1 Apr – 15 Dec	>127	>133	>82.5	>89	>89	-	<165
No_Peeler	1 Apr – 15 Dec	1 Apr – 15 Dec	>127	>133	>82.5	>89	>89	-	-

Source: the table is adapted from the Table 1 in (Bunnell et al., 2010).