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

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ARTICLE

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Abstract
We integrated two existing biological models and a newly developed economic demand model to evaluate the biological and economic performance of alternative policies in the Chesapeake Bay blue crab *Callinectes sapidus* fishery subject to the requirement that yield and revenue be sustainable. The resulting model was able to compare outcomes of alternative management scenarios considered by policy makers. In order to provide insights into the impacts of relevant policy components in a management scenario, we regressed the sustainable outcomes, sustainable yield, and sustainable revenues on a set of policy components. A short fishing season for female crabs combined with a long fishing season for males appeared to increase sustainable yield and revenue. Among size limit policies, lower minimum limits for males, females, peelers, and soft-shell crabs appeared to reduce sustainable outcomes, while a restrictive maximum size limit for mature females seemed to improve fishery performance with respect to both sustainable revenue and sustainable yield.

Fisheries throughout the world have experienced overexploitation for decades (Botsford et al. 1997; Jackson et al. 2001; FAO 2009). In response, fisheries managers have implemented measures to maintain the biological health of the resource to achieve maximum sustainable yield (MSY) or a threshold for spawning potential of the stock. Typically, fisheries managers use a set of several policy components to limit harvest. For example, a limit on the total allowable catch may be accompanied by vessel size limits, fishing gear restrictions, fishing season length restrictions, fishing season closures, size limits, and/or spatial closures (Smith et al. 2008; Anderson and Seijo 2010; Smith 2012). From the biological point of view, some policies intended to reduce fishing mortality have resulted in a recovery of fishery abundance and recruitment to the population (Pala 2010).

In addition to biological effects, the economic outcomes associated with fishery regulations are of interest. Smith and Wilen (2003) argued that isolating economic incentives from fisheries policy making may be inadequate and misleading, since fishers' behavior may offset effects of fishery policies. For example, Smith et al. (2008) concluded that fishers' responses to seasonal closures undermine the effects of the regulation. This phenomenon has also been studied in Homans and Wilen's (2005) analysis of regulated open-access fisheries.

When fisheries managers make their decisions, they often want to obtain information about possible outcomes before the

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fisheries policies are implemented. A variety of frameworks have been built to carry out such evaluations, including life history modeling (see Deacon 1989; Heppell et al. 2006; Smith et al. 2008; Tahvonen 2009a, 2009b; Diekert et al. 2010; Macher and Boncoeur 2010) and management strategy evaluation (see Dichmont et al. 2008; Needle 2008; Bastardie et al. 2010; Jardim et al. 2010; Ives et al. 2013). Despite the insights provided by previous studies, the literature lacks evaluations of the effects of suites of policy options on fishery outcomes. Most studies of fishery policies focus on a specific fishery policy component, such as size limit (Deacon 1989), season closure (Smith et al. 2008), and gear restriction (Tahvonen 2009a; Macher and Boncoeur 2010). In contrast, Griffin and Woodward (2011) evaluated the biological and economic consequences of a range of policies directed at the Gulf of Mexico Red Snapper *Lutjanus campechanus* fishery.

This paper studies the biological and economic consequences of various policies for the blue crab *Callinectes sapidus* fishery in Chesapeake Bay. The stock of blue crab has declined in recent decades, to a large extent due to overfishing (Lipcius and Stockhausen 2002; Aguilar et al. 2008; Miller et al. 2011). To cope with this problem, a range of policies have been implemented since 2001 (Miller 2001). Historically, the fishery has been managed using a complex set of regulations that include combinations of season, gear, size, spatial, and daily harvest regulations. In particular, management agencies developed regulations (primarily daily commercial harvest limits, reduction in the length of the season for female crabs, and closure of the winter dredge fishery in Virginia) to reduce fishing mortality rates on female blue crabs in 2008 by approximately 30% (Miller et al. 2011). While these changes in management initially appeared to be successful in increasing abundance of females, recruitment, and harvest (Miller et al. 2011), harvest during the past two fishing seasons (2013 and 2014) has been among the worst on record. Thus, considering alternative management options is warranted.

We developed a model of the Chesapeake Bay blue crab fishery by integrating two existing biological models and a new economic model to examine the effects of various fishery management scenarios. When combined, these models provided a framework for simultaneously assessing the effects of a set of policies. Our model used the available empirical foundation and estimates of how prices respond to specific policies to allow for a more complete assessment of economic outcomes. Using the integrated model, we were able to investigate the impacts of different combinations of policy components and to estimate the relative effects of each component on the biological and economic outcomes in the fishery.

BACKGROUND ON THE CHESAPEAKE BAY BLUE CRAB FISHERY

The blue crab is an iconic species in Chesapeake Bay and the greater Mid-Atlantic Region and is a crucial component of the Chesapeake Bay ecosystem. The Chesapeake Bay is the largest source of blue crabs in United States, accounting for about 50% of the nation's blue crab harvest (Miller et al. 2011). Economically, blue crab is the largest commercial fishery in Chesapeake Bay (Miller et al. 2011) with a market value of US$46–103 million annually (Bunnell et al. 2010).

In Chesapeake Bay, both male and female blue crabs in different life stages can be harvested, even though there are some restrictions imposed by regulatory agencies. The fishery is managed by three separate agencies: the Maryland Department of Natural Resources (MDNR), Virginia Marine Resource Commission (VMRC), and the Potomac River Fisheries Commission (PRFC). Although these entities agreed in 2001 to implement a unified management strategy based on biological reference points (Miller 2001), policies vary somewhat across jurisdictions.

The policies adopted to manage the blue crab fishery include season closures, size limits, and gear restrictions. Currently the crab fishery is closed from November or December until March or April of the following year, depending on jurisdiction. In recent years, the management strategy has leaned towards protecting female crabs using a shortened season and short within-season closures for female crabs (Bunnell et al. 2010; Miller et al. 2011). Size limits vary by jurisdiction, season, and market category. In 2009, for example, the minimum size limit for males and immature females was 127 mm before July 15 and 133 mm thereafter in Maryland, while this limit did not change in Virginia. The minimum size limit for peelers was set to 82.5 mm before July 15 and 89 mm thereafter both in Virginia and Maryland. Here, peelers refers to crabs in the premolt stage that have a visible shell formed under their existing shell and are close to molting. The minimum size limit for soft-shell crabs was 89 mm and did not change during the fishing season in both regulatory agencies. There was no size limit for mature female crabs historically. There are a number of gear types that are legal for harvesting blue crabs such as crab pots, dredges, and trotlines, which vary temporally and spatially across the management jurisdictions. The VMRC has established some sanctuary areas in the lower part of Chesapeake Bay to protect spawning females. The sanctuary areas are usually closed during the spawning period.

Because of differing quality, the market prices for blue crabs in the different categories vary widely. The most valuable crabs are soft-shell crabs and peelers, which are caught during or immediately after molting. The #1 males are larger and more valuable than #2 males. Females are not graded by size; usually they are smaller than #1 males. Blue crabs that are less marketable and not classified by sex are reported as "mixed" in Maryland and "unclassified" in Virginia.

The complexity of blue crab management structure makes designing and assessing management measures challenging, particularly in terms of understanding interactions among different measures and effects on different objectives. In the next section, we present a model evaluating a set of policies in terms of both biological and economic outcomes that could be useful to managers.

TABLE 1. Management scenarios for the Chesapeake Bay blue crab fishery implemented by regulators or evaluated in Bunnell et al. (2010). The table is adapted from Table 1 in Bunnell et al. (2010); the columns are policy components, and each row constitutes one of the management scenarios (scenarios beginning with date are given as month/day). The first six rows reflect actual sets of policies implemented by the states of Maryland and Virginia. The remaining nine management scenarios are variations considered by Bunnell et al. (2010).

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

AN INTEGRATED BIOECONOMIC MODEL

Our integrated model seeks to evaluate the importance of the different policy components listed in the columns of Table 1 in terms of sustainable yield and sustainable revenue. The first six rows of Table 1 present management scenarios that were implemented by MNDR and VMRC. The rest of the management scenarios are hypothetical.

It is reasonable to assume that the population of blue crab in Chesapeake Bay is independent from neighboring populations (Miller et al. 2011). Both biologically and economically, we treated the Chesapeake Bay blue crabs as independent; they were modeled as a unit population, and the harvested crabs were only for the local market. The model, which is represented in Figure 1, has three main components. First, we used the individual-based simulation model of Bunnell et al. (2010) and Bunnell and Miller (2005) to predict the policy effects on an age-structured population and the harvests of each of the five market categories. Each individual in the model represented a "superindividual." This is consistent with the recent suggestions in the fisheries economics literature that fish stocks should be modeled as a heterogeneous population with a range of ages and/or sizes instead of as a uniform biomass, and policy instruments should be designed accordingly (Tahvonen 2009a; Smith 2012).

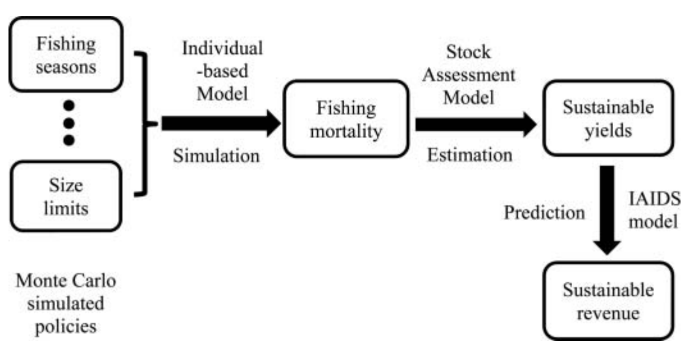

FIGURE 1. Flowchart depicting the key components and paths of the integrated bioeconomic model for the Chesapeake Bay blue crab fishery.

Second, we used a stock assessment model recently developed for this fishery (Miller et al. 2011). Hence, our model responded to recent studies (Wilen 2000; Smith et al. 2008; Diekert et al. 2010) that criticized fisheries economists for too often using overly simplistic biological assumptions without sufficiently rigorous empirical foundations. Like Ives et al. (2013) and Maravelias et al. (2010), we used a fully developed stock assessment model that yielded MSY-based reference points.

Finally, to predict the economic consequences of different policies, we used a new demand analysis for blue crab in Chesapeake Bay in which the demand for each market category was estimated using the Inverse Almost Ideal Demand System (IAIDS) (Eales and Unnevehr 1994). In the next sections we provide more detail on each of the model components and how they were integrated to develop our predictions of the outcomes of different policies both in terms of sustainable harvests and revenues.

Individual-Based Model

The first model upon which we built is an individual-based model developed by Bunnell and Miller (2005) and Bunnell et al. (2010). The model is a sex-specific, per-recruit model that numerically simulates growth, maturity, and mortality of blue crabs on a daily basis over 2 years. For each management scenario, the model simulates a cohort of individuals, in which each individual represents a large number of blue crabs (i.e., superindividual). The initial size for each superindividual is randomly drawn from a lognormal distribution. The model starts simulating the fate of cohorts of individuals at January 1 of the first year and ends at December 31 of the second year.

Blue crabs grow through the process of molting. Whether an individual molts and how much it grows depends on its size and recent water temperature (accumulated growing degree-days). Once the accumulated degree-days reach a stochastic, length-specific threshold, the blue crabs will molt. The crabs become soft-shell status on the day of molting and the following day, and then return to hard-shell status. The peeler shell status occurs a week before molting.

For each day, the number of blue crabs harvested or that die in a cohort is determined by fishery restrictions, the natural mortality rate, and the nominal fishing mortality rate. The model simulates each management scenario with a fixed number of recruitment crabs, and we assumed that the fishers' behavior (i.e., effort) does not respond to different policies. Thus, we selected a constant nominal mortality rate for every management scenario we evaluated in this study. The nominal fishing mortality rate in Bunnell et al. (2010) was selected among various proposed values for each management scenario such that it results in both sustainable spawning potential greater than 0.2 and high revenue. We selected the value 2.9 that Bunnell et al. (2010) used in their model. We also did sensitivity analysis for different nominal fishing mortality rates. The discussion of sensitivity results are presented in the Results and Discussion.

The annual nominal fishing mortality rate captures the probability that each of the superindividuals will be harvested during the year, independent of a set of policies in the model. Which blue crabs can legally be harvested is determined by policy components simulated. Since fishing mortality rate is constant for all management scenarios, variations in the harvests are initially a result of changes in the policies that define which crabs can be legally harvested on a given day. Each management scenario, then, determines which crabs are retained, sold, and exit the biological model. Since the nominal rate is constant, the impacts of modeled fishery policies in different scenarios are comparable and the biological outcomes are most appropriately reported in relative terms.

We ran the individual-based model thousands of times, altering multiple fishery policy components in each run. At the end of each run, realized age- and sex-specific fishing mortality rates were calculated for later use in the stock assessment model. These rates were calculated using a reorganization of the Baranov catch equation (Quinn and Deriso 1999; Bunnell and Miller 2005):

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

where C_{st} equals the total number of crabs harvested for each sex $s, s \in \{m, f\}$, and each age $t, t \in \{0, 1\}$. Blue crabs in the first year are age 0, while crabs in the second year are age 1. The term N_{st}^{0} represents the number of blue crabs alive at the beginning of each fishing season by sex, and N_{st}^{T} represents the number of blue crabs alive at the end of each year by sex. The realized fishing mortality rates, F_{st}, are the key variables connecting the individual-based model and the stock assessment model.

Stock Assessment Model

The second part of our model used the blue crab stock assessment model described in Miller et al. (2011). It is a statistically fitted population dynamics model that estimates the abundance, fishing mortality rates, and sustainable harvest levels of Chesapeake Bay blue crabs. The model tracks cohorts of blue crabs by sex through two age-classes, age 0 and age 1+ (age-1 and older crabs). A penalized maximum likelihood approach was used to estimate the parameters of the model including the stock–recruitment parameters and fishing mortality rates over time, as well as catchability and selectivity for the surveys. The model was fitted to data from the harvest and three fishery-independent surveys that are conducted annually in Chesapeake Bay: the Virginia Institute of Marine Sciences trawl survey, the MDNR trawl survey, and the Winter Dredge

Survey. The model then determined equilibrium sustainable yield based on the estimated parameters by integrating the sex-specific stock–recruitment model with models based on spawning stock biomass per recruit and yield per recruit (Shepherd 1982; Miller et al. 2011).

In our integrated model, parameters estimated in the stock assessment model were combined with the fishing mortality rates taken from the individual-based model to calculate sustainable yield associated with a particular policy setting. The formulas calculating sustainable yield (*SY*) were adapted from Miller et al. (2011):

$$SY = \frac{x_s\left(\ln SPR_f + \ln \alpha + \sigma_R^2/2\right)}{\beta\sum_s SPR_s} \sum_s\left(\frac{F_{s1}}{M+F_{s1}}e^{-(M+F_{s1})} + \frac{F_{s0}}{M+F_{s0}}\left(1-e^{-(M+F_{s0})}\right)\right), \quad (2)$$

where SPR_s is sex-specific spawners per recruit determined as:

$$SPR_s = \frac{x_s e^{-((1+\kappa)M + F_{s0} + \kappa F_{s1})}}{1-e^{-(M+F_{s1})}}. \quad (3)$$

In these equations, the fishing mortality rates, F_{st}, are those associated with a specific management scenario as modeled using the individual-based model. Other parameters of the model are either selected based on expert opinions or estimated in the stock assessment model. The values and descriptions of key parameters are shown in Table 2. Using this two-part biological model, we were able to estimate the sustainable yield predicted by the stock assessment model that followed from any management scenario simulated in the individual-based model.

TABLE 2. Values of key parameters from the stock assessment model for the Chesapeake Bay blue crab fishery (from Miller et al. 2011).

Parameter	Description	Value
	Predetermined	
x_s	Sex ratio (female : male) at recruitment	0.520
κ	Proportion of mortality before spawning	0.370
M	Natural mortality rate	0.900
	Estimated	
α	Stock–recruitment parameter	26.673
β	Stock–recruitment parameter	0.052
σ_R	SD for recruitment	0.339

The Economic Component: Inverse Almost Ideal Demand System

To add an economic measure to our analysis, we included a demand model from Huang (in press) to estimate the prices for different market categories that would result from each management scenario. For products such as fresh vegetables and fish, inverse demand systems are good choices, because the causality goes from quantity to price in these markets (Barten and Bettendorf 1989; Eales and Unnevehr 1994; Holt 2002; Thong 2012). When we model inverse demand systems, the quantities are explanatory variables, while the prices or some price formations are dependent variables. We chose the inverse almost ideal demand system (IAIDS) model developed by Eales and Unnevehr (1994). This model was derived from economic theory and is empirically suitable for exploring the structure of a market that consists of multiple commodities.

Our demand model differs from that used in Bunnell et al. (2010). They developed an inverse demand model that regresses market prices for four market categories on quantities, seasonal dummies, and disposable income. However, their demand model was constructed with constant slopes and lacks cross-price effects that would allow us to investigate market relationships between market categories. Hence, in our model the prices of the different market categories were allowed to affect each other.

Demand for fish and shellfish usually exhibits seasonality due to seasonal variation in demand (e.g., tourism) and the species' biological characteristics. Our demand analysis modified the IAIDS model to investigate seasonal effects in the demand. The system of equations for all commodities is represented as

$$w_i = \alpha_i + \sum_m \lambda_{im} D_m + \sum_j \gamma_{ij} \ln q_j + \beta_i \ln Q, \quad (4)$$

where w_i is the expenditure share for commodity i, $i = 1, \ldots, n$, which is calculated as: $w_i = p_i q_i / \Sigma_{j=1}^{n} p_j q_j$, where p_i is price and q_i is quantity; $\ln q_j$ denotes the logarithm of quantity for the jth commodity, $j = 1, \ldots, n$; D_m represents the incorporated seasonal dummies; and $\ln Q$ is represented as the following form:

$$\ln Q = \alpha_0 + \sum_j \left(\alpha_j + \sum_m \lambda_{jm} D_m\right) \ln q_j + \frac{1}{2}\sum_i \sum_j \gamma_{ij} \ln q_i \ln q_j. \quad (5)$$

Equations (4) and (5) together form an estimable nonlinear system of equations. Since there is difficulty in estimating the parameter α_0 in the nonlinear model, we set α_0 to zero (Deaton and Muellbauer 1980; Moschini et al. 1994). Equation (4) indicates that the expenditure share of market category i is affected not only by its own quantity, $\ln q_j$, where $j = i$, but also by the quantities of other categories in the same market, ln q_j, where $j \neq i$. The seasonal variable D_m captures systematic demand shifts across seasons. The system of equations (equation 4) is estimated with the nonlinear seemingly unrelated regression method. To avoid the singularity problem, an equation has to be dropped for estimation. The coefficients of this equation are recovered from following relationships in the demand system: $\Sigma_i \alpha_i = 1$, $\Sigma_i \gamma_{ij} = 0$, $\Sigma_i \beta_i = 0$, and $\Sigma_i \lambda_{is} = 0$ over commodities

It is not straightforward to interpret the estimated parameters (α, β, γ, and λ) in the demand system (equations 4 and 5). However, they can be used to estimate the more easily understood price and scale flexibilities, f_{ijm} and f_{im}. A price flexibility is an estimate of the percentage changes in price for category i in response to a 1% change in the quantity of category j in season m. A scale flexibility indicates the percentage change in the normalized price i (i.e., price divided by expenditure) due to a scale expansion for all categories in the system (Park and Thurman 1999). The steps required to derive the flexibilities are discussed in Eales and Unnevehr (1994). Here, we only present the resulting formulas that estimate flexibilities,

$$f_{ijm} = -\delta_{ij} + \frac{\gamma_{ij} + \beta_i\left(\alpha_j + \lambda_{jm} + \sum_k \gamma_{kj} \ln q_{km}\right)}{w_{im}}, \quad (6)$$

$$f_{im} = -1 + \frac{\beta_i}{w_{im}}, \quad (7)$$

where δ_{ij} is the Kronecker delta ($\delta_{ij} = 1$ if $i = j$; otherwise $\delta_{ij} = 0$) and w_{im} is the share of expenditures on blue crabs that went to category i. The price of each market category is affected by the quantities all the categories in the market. We assumed that the cross-category effects are multiplicative.

The data used to estimate the demand system were monthly time series from 1994 to 2007. The monthly harvest data were combined from logbook records of crab fishers from MDNR, and the monthly price data were from MDNR monthly survey of seafood dealers. Since there is no category-specific data for Virginia, we assumed the demand structure of blue crab in Maryland is representative for Chesapeake Bay, as in Bunnell et al. (2010). In the data set, the prices are converted to the real prices by the consumer price index (CPI) in which the base CPI is equal to 100 in 1982. The monthly quantity and price data range from April to November for each year. To account for seasonality, we introduced dummy variables by grouping April and May as spring, June to August as summer, and September to November as fall. Since the data do not capture different sizes within a market category, the model was not able to capture the policies' impacts on prices achieved by changing the average size within a category.

Integrating the Biological and Economic Components

The integration of the three models into our integrated model is represented in Figure 1. The specific steps are as follows:

1. For a single management scenario, the individual-based model simulates the life history of all individual blue crabs over 2 years. At the end of the simulation, the model predicts age- and sex-specific blue crab harvests under this management scenario. According to the realized outcomes, we estimated fishing mortality rates for both sexes and ages using equation (1).
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 estimated the annual sustainable yield associated with this management scenario by equations (2) and (3), which use parameters from the stock assessment model. In this step, we decomposed the annual sustainable yield into monthly sustainable yield over 2 years for each category based on the proportion of category harvests from the individual-based model. The final monthly sustainable yield is the summation of sustainable yield in the same month of first year (age-0 crabs) and second year (age-1 crabs).
3. The monthly prices for all market categories are predicted by the demand model, given the sustainable yield. Since we used estimated flexibilities to explore how price changes in response to quantity changes, we needed to specify a base scenario with prices and quantities. We chose monthly prices of the latest year from the fishery data as our base prices. For base quantities, we chose a specific simulated scenario that generated monthly sustainable yield. Because the scales of the biological and demand models are different, we were not able to accurately predict actual prices for the different categories. Hence, all economic outcomes should be interpreted in relative terms.

Performance Measures and Evaluation

For our discussion, two measures for management scenarios were chosen to evaluate the relative performance of different policy components: aggregate sustainable yield and aggregate sustainable revenue. Sustainable yield was selected because it assesses biological outcomes of different fishery management scenarios. Sustainable revenue measures the ability of policy components to achieve economic outcomes while maintaining yield at sustainable levels.

However, these are not perfect performance measures. First, these measures are equilibrium measures and, therefore, do not account for relative trade-offs along a dynamic path to the equilibrium. Second, sustainable *net* revenue would be a better criterion for measuring economic outcomes compared with sustainable revenue. Costs to the industry are likely to vary significantly for different policies. For instance, changing size limits requires fishers to replace or modify their fishing gears while season closures can reduce fuel consumption. Similarly, a restrictive size limit or exclusion of female crabs from harvest may force a fisher to discard a substantial portion of the crabs caught, thereby increasing the unit cost for those crabs that are retained. Unfortunately, we are not aware of any suitable data sets to estimate costs associated with the blue crab policies. This could be an area for future study. Finally, for the current analysis we only focused on the suppliers' side of the benefits evaluation, ignoring differences in the consumers' side.

The process described above was used to evaluate the performance of any management scenario that can be simulated using the individual-based model. We started by evaluating the management scenarios listed in Bunnell et al. (2010), as presented in Table 1. In order to disentangle the effects of each policy component, we then created 4,000 hypothetical management scenarios using the Monte Carlo methods. We assumed that the policy components form a multidimension space, in which we sampled management scenarios with uniform distribution for each component. For instance, we set the start date for male crab fishing within the range between March 15 and April 1, in which the start date randomly selects a value for a management scenario. Other policy components are determined in the same manner. In this way, we were able to create sufficient variation to estimate the marginal effects of different policy components.

RESULTS AND DISCUSSION

Demand Estimation

We first present results from our demand model. Since parameters directly estimated from equations (4) and (5) have no straightforward economic meanings, the coefficient estimates are presented in Table A.1 in the Appendix. The estimates that are most interesting are the season-varying flexibilities estimated from equations (6) and (7). The flexibility estimates and associated standard errors are presented in Table 3. A commodity is classified as a necessity if its scale flexibility is less than −1, or defined as a luxury if greater than −1 (Eales and Unnevehr 1994). Blue crabs in Chesapeake Bay appear to be economic necessities for all categories, except for soft-shell and peeler crabs. According to the interpretation of scale flexibility, blue crabs in Chesapeake Bay for all categories except for soft-shell crabs and peelers appear to be economic necessities, meaning that a 1% increase in the consumption of all categories would lead to a decrease in the normalized price of these categories, but the decrease would be greater than 1%.

The own-price flexibility indicates how the price of a commodity changes in response to its own quantity. Demand for a commodity is said to be flexible if the own-price flexibility is negative and greater than one in absolute value. Most of the estimated own-price flexibilities are less than one in absolute value and have the expected signs, indicating that a 1% increase in blue crab quantities results in less than 1% decline in corresponding prices. However, there are some unexpected results for own-price flexibilities, such as female crabs in summer, and soft-shell crabs and peelers in fall. This may be due to substantial decreases in landings for these categories during these periods.

Cross-price flexibility indicates how the price of one commodity responds to the quantity change of another. Negative cross-price flexibility indicates the two goods are substitutes, while the positive number denotes complements. Two products are substitutes if a price increase in one product leads to quantity increase in the other good, and complements is when the opposite occurs. All significant cross-price flexibilities in our estimates are negative, which indicates that the five blue crab market categories are substitutes over seasons.

Policy Simulation Results

Using the integrated model, we were able to simulate the impacts of a wide range of possible policy combinations. We first evaluated the performance of management scenarios analyzed in Bunnell et al. (2010), which are presented in Table 1. These scenarios are labeled in Figure 2, which presents the outcomes with sustainable yield on the horizontal axis and sustainable revenue on the vertical axis. The remaining dots in the figure come from the 4,000 policy scenarios that were randomly created drawing each policy component from a range that roughly corresponds with those included in the Bunnell et al. (2010) scenarios. A large sustainable revenue is possible at each attainable level of sustainable yield (Figure 2).

As seen in Figure 2, the simulated scenarios fall into two groups, which differ in the relative revenue achieved for a given level of harvest. Of the 15 scenarios used by Bunnell et al. (2010), only two yielded outcomes that fall outside the right cluster: 152_MinFemCW and No_Peeler. The 152_MinFemCW, which yields the lowest sustainable yield, is the only Bunnell et al. (2010) scenario that includes a minimum size limit on mature females. In fact, all of the simulated scenarios that fall in the cluster on the left have a minimum size limit on female crabs. As that limit increases, sustainable harvests tend to decline. The other outlier among the Bunnell et al. (2010) scenarios is the No_Peeler scenario, which prohibits peeler crab harvest, resulting in the lowest sustainable revenue, which is not surprising since peeler and soft-shell crabs are the most valuable market categories.

It is of interest to identify the management scenarios that result in both high sustainable yield and sustainable revenue, as represented by the upper right dots in Figure 2. Among the scenarios listed in Table 1, three satisfy this criterion: 2008MDRegs, 2009MDRegs, and 10/1–12/15_FEM. These three scenarios have more restrictions on the fishing season for female crabs in terms of early end-date or within-season

TABLE 3. Seasonal flexibilities for five categories in the Chesapeake Bay blue crab market. Three asterisks denote 1% significance, two asterisks denote 5% significance, and one asterisk denotes 10% significance; SE values are presented in parentheses.

	#1 male price change			#2 male price change			Female price change			Soft-shell and peeler price change			Mixed price change		
Quantity change	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
#1 male	−0.624***	−0.705***	−0.655***	−1.017***	−0.524***	−0.780***	−0.443***	−0.579***	−0.194***	−1.185***	−0.170	−0.614	−0.571**	−0.451**	−0.537**
	(0.085)	(0.070)	(0.082)	(0.233)	(0.109)	(0.158)	(0.135)	(0.160)	(0.051)	(0.313)	(0.185)	(0.723)	(0.246)	(0.188)	(0.223)
#2 male	−0.006	−0.014	−0.016	0.147	−0.448***	−0.448***	−0.127*	−0.166**	−0.054**	−0.058	−0.048	−0.218	0.035	0.027	0.033
	(0.034)	(0.028)	(0.033)	(0.108)	(0.052)	(0.052)	(0.067)	(0.082)	(0.027)	(0.054)	(0.070)	(0.258)	(0.117)	(0.092)	(0.110)
Female	−0.167***	−0.155***	−0.227***	−0.067	−0.042	−0.107	−0.041	0.168*	−0.626***	−0.236***	−0.305***	−0.701*	−0.158	−0.125	−0.149
	(0.041)	(0.033)	(0.039)	(0.125)	(0.061)	(0.090)	(0.076)	(0.095)	(0.032)	(0.071)	(0.095)	(0.364)	(0.132)	(0.104)	(0.126)
Soft-shell and peeler	−0.199***	−0.135***	−0.135***	−0.308***	−0.117***	−0.143***	−0.224***	−0.234***	−0.070***	−0.481***	−0.390***	1.224***	−0.009	−0.006	−0.006
	(0.033)	(0.027)	(0.031)	(0.093)	(0.038)	(0.050)	(0.055)	(0.056)	(0.016)	(0.062)	(0.092)	(0.386)	(0.094)	(0.059)	(0.061)
Mixed	−0.049	−0.042	−0.045	0.092	0.045	0.072	−0.123*	−0.151*	−0.048*	0.061	0.088	0.301	−0.372***	−0.505***	−0.410***
	(0.037)	(0.030)	(0.035)	(0.118)	(0.057)	(0.083)	(0.072)	(0.089)	(0.029)	(0.059)	(0.076)	(0.280)	(0.126)	(0.099)	(0.118)
Scale	−1.136***	−1.118***	−1.141***	−1.216***	−1.105***	−1.155***	−1.104***	−1.128***	−1.042***	−0.674***	−0.521***	1.046***	−1.004***	−1.003***	−1.003***
	(0.015)	(0.013)	(0.016)	(0.056)	(0.027)	(0.040)	(0.035)	(0.044)	(0.014)	(0.018)	(0.027)	(0.113)	(0.062)	(0.049)	(0.058)

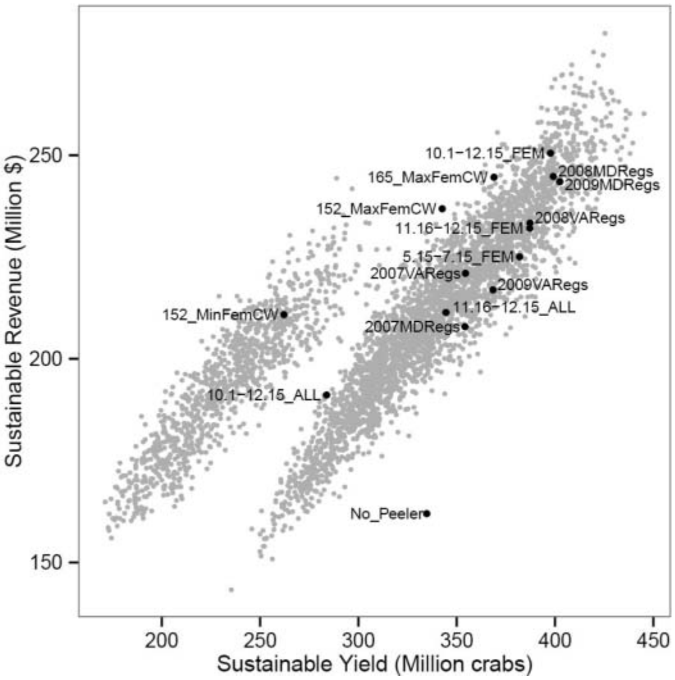

FIGURE 2. Sustainable yield and sustainable revenue for 4,000 sampled scenarios (gray dots) and the 15 management scenarios listed in Table 1 (black dots) for the Chesapeake Bay blue crab fishery.

closures, implying that regulating the harvest of female crabs is probably a good policy. The large number of hypothetical management scenarios can help us identify the effects of the individual management components.

Because of the interactions between the different management components, it is not always possible to see the separate effect of one component at a time. Hence, to evaluate the impacts of various policy components, we used multivariate linear regression of sustainable yield and sustainable revenue on all policy components and their squared and interaction terms. Since the regression with squared and interaction terms has a total of 96 coefficients, the estimation results are not presented. The marginal effects for all policy components evaluated at a certain management scenario, 2009MDRegs, were calculated. The marginal effects can be interpreted as an estimate of the effect on sustainable revenue or sustainable yield of a one-unit change of a policy component, holding all other policy components constant. The results are shown in Table 4. Since sustainable yield and sustainable revenues are relative numbers, the absolute magnitudes of those marginal effects do not represent real values. The standard errors associated with marginal effects are also reported in Table 4. However, the standard errors do not have the normal interpretation since the variance of the parameter estimates approaches zero as the number of simulations goes to infinity. Their relative values, however, do have some meaning. For any number of simulations the policy components with strong effects on the outcomes would tend to be more significantly different from zero than those for which the effect is weak.

The regression results are complemented by the bivariate plots of the simulated sustainable revenue versus six different policy components in Figure 3. As seen in Figure 2, for a given policy regarding the minimum size limit on female blue crabs, there is a strong positive relationship between sustainable revenue and sustainable yield. Hence, the results with regard to sustainable revenue can be used to infer the general impacts on sustainable yield.

Fishing Season Length

Regulations on fishing season length are widely used for the blue crab fishery in Chesapeake Bay. Fishing is currently prohibited during the winter. Usually, the fishing season starts around April 1 and ends around December 15. We

TABLE 4. Marginal effects of policy components for the Chesapeake Bay blue crab fishery. The contents in the parentheses associated with policy instruments in column 1 are units for the explanatory variables. The delta symbol (Δ) represents change of size limit; M represents male; F represents female; F_0 represents immature female; F_1 represents mature female. Three asterisks denote 1% significance, two asterisks denote 5% significance, and one asterisk denotes 10% significance; SE values are presented in parentheses.

Policy components	Sustainable revenue	Sustainable yield
Start date – M (day)	0.493*** (0.013)	1.233*** (0.020)
Season length – M (days)	0.631*** (0.007)	1.422*** (0.011)
Start date – F (day)	−0.291*** (0.014)	−0.126*** (0.021)
Season length – F (days)	−0.517*** (0.008)	−0.458*** (0.012)
Closure days – F (days)	−0.209*** (0.020)	0.058* (0.032)
Initial minimum size limit – M and F_0 (mm)	−0.258*** (0.042)	−2.442*** (0.065)
Δ minimum size limit – M and F_0 (mm)	−0.064 (0.044)	−1.879*** (0.069)
Initial minimum size limit – peeler (mm)	−1.526*** (0.047)	−0.489*** (0.072)
Δ minimum size limit – peeler (mm)	−1.342*** (0.041)	−0.481*** (0.064)
Minimum size limit – soft-shell (mm)	−0.545*** (0.023)	−0.190*** (0.036)
Maximum size limit – F_1 (mm)	−5.618*** (0.449)	−14.330*** (0.698)
Minimum size limit – F_1 (mm)	−9.726*** (0.761)	−29.027*** (1.182)

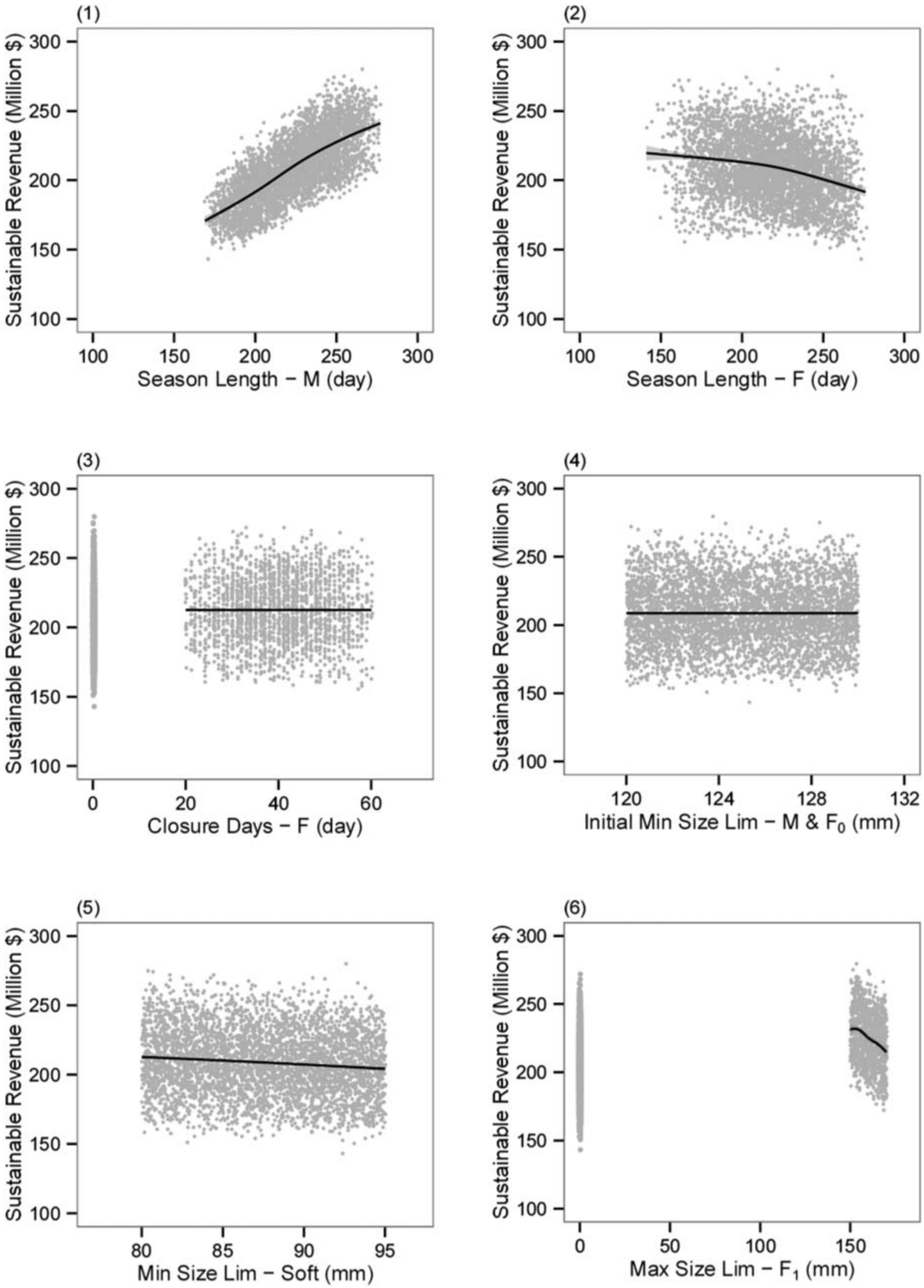

FIGURE 3. Scatter plots of six policy components versus sustainable revenue for the Chesapeake Bay blue crab fishery. Panel (**1**): season length for males; panel (**2**): season length for females; panel (**3**): closure days for females; panel (**4**): initial minimum size limit for males and immature females; panel (**5**): minimum size limit for soft-shell crabs; panel (**6**): minimum size limit for mature females.

independently varied male and female crab fishing season start date and fishing season length as fishing season variables to assess the impacts of these policies. As seen in Table 4, both the marginal effects associated with the male crab fishing season are positive, indicating that making the male crab fishing season longer can result in higher sustainable revenue and sustainable yield. This positive correlation is also seen in panel (1) of Figure 3. In addition, we found that by holding the season length constant, the start date can be postponed, which would increase both sustainable revenue and sustainable yield.

The effect of fishing season for female blue crabs is exactly the opposite of that for males. The estimated marginal effects associated with female start date and fishing season length are all negative. This is seen in both the regression results and in panel (2) of Figure 3, in which a generally downward sloping relationship is evident. Relative to current levels, a shorter season for female crabs leads to greater yield and revenue. Further, holding the season length constant, we found that starting the female crab season earlier would increase sustainable revenue. These results likely arise because a shorter fishing season for female crabs is more effective in preserving the female stock, which is important for stock recruitment.

In addition to the winter closure, female blue crab harvests are also closed in the middle of the season. This type of policy was implemented by Maryland in 2009. Among our scenarios, we simulated the effects of allowing the female crab fishing season to be closed once or twice. Bunnell et al. (2010) found that earlier end-date and within-season closures for female crabs may result in higher revenue than found in scenarios without such policies. However, they did not consider the effects of closure length. In our analysis, we evaluated the effect of the number of closure days on sustainable outcomes. The marginal effects of within-season closure for female blue crabs are negative for the sustainable revenue equation, while positive for the sustainable yield equation. However, based on panel (3) in Figure 3, the closure length does not appear to have much of an effect on sustainable revenue. We should note that, as is true for all the policy components that we evaluated, our model does not allow for fishers to change the temporal distribution of effort around a closure; the results only estimate the direct effects of fishing season closure.

Minimum Size Limit for Hard-Shell Male Crabs

Minimum size limits for males and immature females have been widely used in the Chesapeake Bay blue crab fishery, primarily to protect juvenile crabs. For example, the regulatory agency in Maryland sets the minimum size limit for hard-shell males at 127 mm from the start of the fishing season through July 15 and 133 mm thereafter. However, in Virginia, the minimum size limit remains the same throughout the fishing season.

To evaluate the effect of the size limits throughout the season in our simulations, the minimum size limit at the beginning of the fishing season is first randomly selected. Then, after July 15 the limit either remains the same or increases to a higher level. The marginal effects of the minimum size limit are negative for both sustainable yield and revenue. The results indicate that increasing the minimum size limit at the beginning of a fishing season, i.e., making the policy more restrictive, can lead to lower sustainable yield and revenue. Again, when shown graphically in Figure 3, the effect of this policy component seems to have little discernible impact on sustainable revenue. Increasing the minimum size limit in the middle of a season appears to bring about similar results.

Soft-Shell and Peeler Crab Minimum Size Limits

As with males and immature female crabs, policy makers also place minimum size restrictions on soft-shell crabs and 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). A minimum size limit for soft-shell crabs is usually set for the entire season. In the 2007 Maryland scenario the minimum size limit for soft-shell crabs was 89 mm (Bunnell et al. 2010).

In our simulated results, a minimum size limit for peelers was randomly selected, then the algorithm randomly chose whether to increase the limit on July 15. All simulated scenarios included a minimum size limit for soft-shell crabs, ranging from 80 to 95 mm. The marginal effects of the size limit on sustainable revenue and yield are both negative, suggesting that increasing the minimum size limit is of little benefit to the blue crab fishery. The effect, though not very strong, could be due in part to a limitation of the model. Although all policies change the distribution of crabs across market categories, the model does not allow us to change the size distribution within a category. Hence, it cannot capture the benefits of a policy that leads to larger crabs within a category.

Mature Female Crab Size Limits

In current management, there are no size restrictions for mature female blue crabs. To examine the potential effects of this policy tool, some of our simulated scenarios included maximum or minimum size limits for mature females, as suggested in Bunnell et al. (2010). The purpose of this policy was to protect mature female crabs, which are crucial for spawning.

We considered three different scenarios in terms of mature female crab size limits: scenarios with a maximum size limit, a minimum size limit, or no size limit. In scenarios without a minimum size limit, the minimum size limit variable was set to 0 mm, and in scenarios without a maximum size limit, the maximum size limit variable was set to 250 mm. We assumed that blue crabs cannot exceed a width of 250 mm. The estimated marginal effects associated with mature female crab size limits are large relative to the effects of other policy components, implying that this policy tool may have larger impacts. The use of a more restrictive maximum size limit, i.e., decreasing the limit, leads to higher sustainable revenue and sustainable yield. It appears that the more restrictive maximum size limit protects adult females from being harvested, yielding benefits in terms of harvests and revenue. We also see this in panel (6) of Figure 3; although sustainable revenue can take on a wide range of levels when no limit is imposed, a maximum size limit shifts the distribution upward, and the highest levels are achieved for the most restrictive policy. However, as pointed out in Bunnell et al. (2010), the maximum size limit for mature female blue crabs deserves consideration with caution because the spawning contributions of different sizes of females are unknown. In contrast to a maximum size limit, a more restrictive minimum limit that reduces the number of crabs that can be retained reduces sustainable revenue and sustainable yield, suggesting that the minimum size limit be set at a low level.

Sensitivity Analysis

The model results are somewhat sensitive to the parameters under consideration. Hence, we carried out a sensitivity analysis by running 1,000 simulations for five fishing mortality rates ranging from 2.0 to 3.5. For most policy components, the marginal effect becomes more pronounced as fishing mortality increases. There are, however, some exceptions to this general trend. As fishing mortality increases, the marginal effect of a minimum size limit for males on sustainable revenue and the effect of changing the minimum size limit for peelers in the middle of a season on sustainable yield diminish. For several components, the sign of the marginal effect on sustainable yield changes over the simulated range, e.g., the female crab fishing season length and minimum size limit for peelers. Hence, we concluded that the effect of different policies on sustainable revenue is quite robust. When sustainable yield is the outcome variable of interest, however, results are more sensitive to the specific value of fishing mortality.

CONCLUSIONS

The integrated model we introduced is able to examine the impacts of a wide range of management scenarios on the sustainable yield and sustainable revenue of the Chesapeake Bay blue crab fishery. The modeling strategy connects an individual-based model, a stock assessment model, and an economic demand model, offering potentially valuable insights for managers and an example for fisheries modelers. The integrated framework is able to simulate sustainable biological and economic outcomes corresponding to a wide set of policy components and to estimate the marginal effects of such policy components.

Our analysis gives preliminary indications as to which policy components are likely to be most effective. First, our model indicates that sustainable revenues could be increased if the female blue crab fishing season were shortened and intermittently closed to protect spawning females. Restrictive minimum size limit for males, immature females, and peelers appear to reduce both aggregate sustainable revenue and sustainable yield. For soft-shell crabs, a minimum size limit appears to be unwise since restricting access to these most valuable crabs is costly with no evidence that it would result in higher sustainable yields in the fishery as a whole. For mature females, it appears that a maximum size limit is a better policy than the minimum size limit. While these results are not definitive—any model has serious limitations that must be appreciated—we believe that they can prove helpful to policy makers evaluating how to improve the management of the Chesapeake Bay blue crab fishery.

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Appendix: Additional Information from the Model Equations.

TABLE A.1. The estimated parameters from the IAIDS model for the Chesapeake Bay blue crab fishery. Three asterisks denote 1% significance, two asterisks denote 5% significance, and one asterisk denotes 10% significance; SE values are presented in parentheses.

Equations	#1 male	#2 male	Female	Soft-shell and peeler	Mixed
γ_{i1} (#1 male)	0.233*** (0.036)	−0.029*** (0.008)	−0.059** (0.025)	−0.124*** (0.032)	−0.022** (0.010)
γ_{i2} (#2 male)	0.005 (0.017)	0.039*** (0.004)	−0.018* (0.011)	−0.027*(0.016)	0.001 (0.004)
γ_{i3} (female)	−0.083*** (0.021)	−0.002 (0.004)	0.155*** (0.012)	−0.064*** (0.020)	−0.006 (0.005)
γ_{i4} (soft-shell and peelers)	−0.090*** (0.012)	−0.010*** (0.003)	−0.034*** (0.008)	0.134*** (0.009)	−0.000 (0.003)
γ_{i5} (mixed)	−0.019 (0.019)	0.004 (0.004)	−0.019 (0.012)	0.010 (0.017)	0.024***(0.005)
β_i (translog)	−0.066*** (0.007)	−0.007*** (0.002)	−0.017*** (0.006)	0.090*** (0.005)	−0.000 (0.002)
λ_{i1} (spring)	−0.060 (0.044)	−0.001 (0.009)	−0.014 (0.026)	0.083** (0.040)	−0.008 (0.011)
λ_{i2} (summer)	0.043 (0.029)	0.013** (0.006)	−0.021 (0.017)	−0.033 (0.027)	−0.002 (0.007)
α_i (intercept)	0.601** (0.238)	0.171*** (0.049)	0.033(0.143)	0.073 (0.218)	0.122** (0.059)
R-square value	0.987	0.948	0.980	0.947	