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RESEARCH ARTICLE

Evaluating habitat-fishery interactions: Submerged aquatic vegetation and blue crab fishery in the Chesapeake Bay

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Abstract: This paper investigates habitat-fisheries interaction between two important resources in the Chesapeake Bay: blue crabs and submerged aquatic vegetation (SAV). A habitat can be essential to a species (the species is driven to extinction without it), facultative (more habitat means more of the species, but species can exist at some level without any of the habitat) or irrelevant (more habitat is not associated with more of the species). An empirical bioeconomic model that allows for all three possible relationships was estimated and two alternative approaches were used to test whether SAV matters for the crab stock. Our results indicate that a model that incorrectly assumes that habitat is essential to a species can result in model misspecification and biased estimates of the impact of habitat on species productivity. Using a model that assumes an essential relationship, we find that SAV has a significant positive impact on blue crab productivity ($p < 0.001$). However, in a more general model, we failed to reject the null hypothesis that SAV is irrelevant for crabs in the Bay ($p > 0.05$).

Keywords: empirical bioeconomics, Chesapeake Bay, essential and facultative habitat, blue crabs, submerged aquatic vegetation

1 Introduction

Submerged aquatic vegetation (SAV) constitutes a class of plants (vascular hydrophytes) that grow in shallow shoreline areas of many aquatic systems, including the Chesapeake Bay[1]. This type of vegetation plays a vital role, since it provides habitat and sources of food for many species, including waterfowl, fish and invertebrates[2,3]. Because SAV is considered one of the main health indicators for Chesapeake Bay (Bay hereafter), it is monitored annually and restoration activities regularly occur[4].

One of the species that may be affected by the abundance and spatial distribution of SAV is the blue crab (*Callinectes sapidus*). Blue crabs are of paramount importance to the Bay from both ecological and commercial points of view. Ecologically they are a vital food-web link in the ecosystem because they are major predators of benthic communities, as well as prey for many fish species[5]. Commercially, the long-term (1990-2010 average) harvest of the species coming from the Bay and its tributaries is 75 million pounds of meat. In 2010 the total harvest was estimated at 92 million pounds[5] with more than \$100 million in dock value[6]. Blue crabs can be harvested throughout the Bay, with males found in the mesohaline and oligohaline (medium and low salinity zones, respectively)portions of the estuary in Maryland and upper tributaries, while females prefer the saltier waters in the mainstem and Virginia[5]. Crabs are harvested in the Chesapeake Bay with a variety of gear. Using pots is by far the most common harvesting technique in Virginia[7]. In Maryland and the Potomac, other methods employing gear such as trotlines (trotlines and pots are the most common fishing techniques in Maryland), hand lines, dip nets and dredges are also used[5].

Blue crabs are thought to utilize SAV as a source of food, nursery grounds for juveniles, and shelter during mating and molting. Field and laboratory experiments indicate that the number of juvenile blue crabs is substantially greater when SAV is present than when it is not[8]. In particular, as many as thirty times more young crabs have been counted in SAV, such as eelgrass, than on bare bottom[9,10].

However, SAV in the Bay experienced a big decline between 1960 and the mid-1980s[1], when more than half of the SAV disappeared from the Bay's waters[11]. That loss has been attributed primarily to poor water quality[1,12]. In particular, nutrients trigger algal growth, both in the

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water and upon SAV, preventing sunlight from reaching the plants, resulting in reduced growth and eventually leading to death.

Plots of blue crab abundance (Figure 1) and harvest (Figure 2) over the last twenty-two years show downward trends in both stock and harvest, particularly during the 1990s, followed by a recovery at the beginning of the 21st century. The rapid increase of stock (and harvest) occurred after 2007.

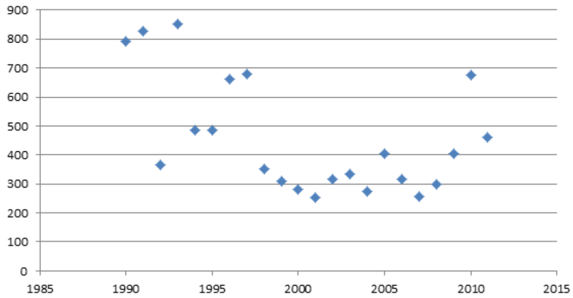

Figure 1. Blue crab abundance (million)[13]

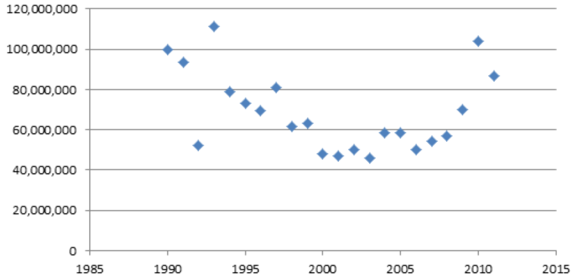

Figure 2. Bay-wide blue crab harvest (pounds)[6]

Interestingly, the rapid recovery of the stock between 2007 and 2010 coincides with an increase in SAV of about 5,000 hectares, as Figure 1 demonstrates.

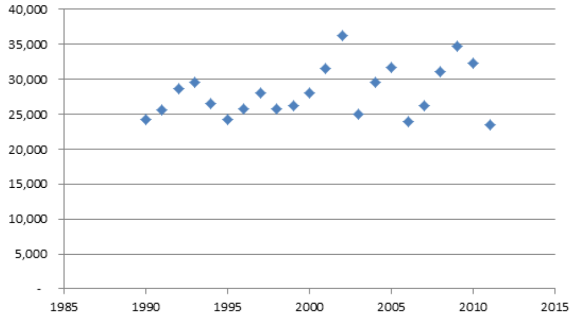

Figure 3. Bay-wide SAV coverage (hectares)[14]

Nonetheless, the SAV pattern over the last 22 years can be characterized as fluctuating, generally decreasing without the same peaks and valleys as the blue crab stock pattern. SAV data taken from the Virginia Institute of Marine Science suggest that during the period 1990-2011 the Bay experienced an average annual loss of about 40 hectares. The fact that SAV and blue crab stock do not follow the same pattern is not necessarily an indicator that SAV does not play an important role for the species, as tides, water currents, water temperature, changes in salinity due to irregular precipitation and other stochastic processes also may be responsible for fluctuations in blue crab dynamics[15]. The species has a tight link with environmental factors other than SAV. These environmental factors are being affected by global climate change, the exact influence of which on species' recruitment is largely unexplored[15].

Two research questions emerge from the above discussion: how important is SAV for blue crabs in the Bay and what are the productivity impacts on the fishery from observed changes in SAV? In their review of habitat-fishery theoretical and empirical bioeconomic studies, Foley *et al.*[16] classify the modeling approaches based on how species' habitat is treated. In particular, a habitat is classified as either essential or facultative. Facultative habitat increases the productivity of a species, but does not lead to its extinction if the habitat is completely eliminated[16]. In contrast, if the habitat is essential, then the species cannot survive without at least some of the habitat. A third possibility that Foley *et al.* did not consider is that the identified habitat may be irrelevant to the species. That is, the abundance or productivity of the species may be unaffected by changes in habitat. These are empirical issues that make our first research question interesting and important. If SAV is found to be essential, that would be a valuable piece of information for environmental managers and policy makers, and would elevate the importance of protecting and restoring SAV.

Turning to the second research question, our objective is to quantify productivity changes in the blue crab fishery triggered by changes in SAV. In particular, the extent to which changes in SAV affect fishing effort, harvest and revenues in equilibrium will be quantified.

Using an empirical bioeconomic model for this paper it is important to review two strands of literature: one that assumes that habitat matters to the productivity of a species and another that empirically tests whether and to what degree habitat matters for the species in question. Both strands of literature, to some extent, estimate welfare changes coming from habitat-fisheries interactions and linkages. Starting with the first strand of literature, Lynne and colleagues[17] quantified the effect of the marsh area of Florida's Gulf Coast on the economic productivity of blue crabs. Their main finding was that alternative levels of both effort and marsh affect the marginal value productivity of marsh. In one of the first empirical bioeconomic studies for the Bay, Kahn and Kemp[1] estimated the lower bound of a damage function related to losses in SAV. Their analysis addressed the shelter SAV provides to striped bass. Welfare changes are measured in terms of producer and consumer surplus. The work by Anderson[18] is similar to that of Kahn and Kemp but the author dealt with the other side of the coin, quantifying the economic benefits of restoring the blue crab's preferred habitat in Virginia's portion of the Bay. The preferred habitat was, however, narrowed down to seagrass. The net benefit was found to be \$1.8 and \$2.4 million per year for producers (fishermen) and consumers, respectively[18]. The results were obtained through simulation instead of via direct estimation.

Some authors have acknowledged the importance of wetland as habitat for blue crabs at the Gulf Coast[19]. They analyzed the effects of wetland increase on the species and its value, and quantified this impact with changes in producer and consumer surplus. A big assumption was that the resource was sole-owned. Later on, Freeman[20] addressed the same topic and application under the alternative management regimes of sole ownership and open access, showing that the marginal value of the resource will not always be lower under open access compared to sole ownership[20]. In both studies, stock was a function of habitat. A more recent study[21] has considered the impact of different oyster management regimes on the blue crab fishery in the Chesapeake Bay. In that study the abundance of oysters was modeled to increase blue crab's carrying capacity, as habitat and shelter against predation for juvenile crabs.

To our knowledge, few studies related to fisheries-habitat interactions test whether and to what degree habitat matters. Swallow[22] indirectly tested the importance of habitat by formulating two resource sectors, one renewable (fishery) and one non-renewable (land development). The non-renewable resource applied to the drainage of wetland near coastal areas, affecting brown shrimp productivity through changes in water salinity. The stock was affected only through its habitat, which deteriorated due to irreversible land development (drainage of wetland). The important trade-off between preservation and development of wetlands was then empirically examined[22]. Of particular relevance to this paper is the recent study by Foley and colleagues[23]. By applying the production function approach, the authors estimated the association between cold water corals and redfish fishery in Norway, without assuming a particular relationship (essential versus facultative) between habitat and the resource stock. Instead, they estimated two models, one with essential and one with facultative habitat, and demonstrated that the essential habitat model fit the data better[23]. Moreover, due to lack of habitat data, the authors estimated annual losses in harvest associated with different scenarios of habitat degradation.

In their important contribution, Barbier and Strand[24] addressed the impact of mangrove systems as essential habitat (breeding and nursery grounds) for shrimps in Campeche, Mexico. The authors developed an open-access fishery model, where mangrove area was assumed to enhance the carrying capacity of the stock and therefore the production and value of harvest in the fishery[24]. Later on, Barbier *et al.*[25] formulated a dynamic production function under an open-access setting in their attempt to quantify the effect of mangroves on the artisanal marine demersal and shellfish fisheries in Thailand. Their model also treated habitat as essential, assuming a positive spillover of mangroves on species' carrying capacity. Others[26] adopted the same approach for Southern Thailand, while others[17] incorporated lagged effects in their approach.

The contributions of this research are threefold. First, we provide a general methodology for testing the importance of a potential fisheries habitat on the species in a way that allows for the possibility that the habitat plays no role. In particular, our model will be general with regards to the role played by SAV in the blue crab population, and statistical tests will be conducted to determine whether SAV is essential habitat, facultative habitat or irrelevant for crabs. Second, we develop and apply two alternative ways of testing the role of a habitat. Although relatively simple, the two ways have never been used before and can validate (or challenge) the results of the more sophisticated model. Finally, our empirical bioeconomic model is estimated, and habitat-fisheries interactions are quantified for two of the most important resources (SAV and blue crabs) in the largest estuary in United States, the Chesapeake Bay. In particular, comparative static effects in equilibrium of changes in harvest, effort and revenues triggered by SAV changes are calculated.

2 Materials and methods

2.1 A habitat-fisheries interaction model

Our model is based on Barbier and Strand, and Foley *et al.*[23,24] We begin with blue crab stock dynamics. With $E$and Sbeing the fishing effort and SAV, respectively, the equation of motion for the crab stock (C) can be expressed in a standard manner as

$$\dot{C} = F\left(C, S\right) - h\left(C,\ E\right) \tag{1}$$

where $h(.)$ stands for harvest as a function of the crab stock and the amount of fishing effort. The Schaefer production function is $h\left(C,\ E\right) = qEC$, with q being the constant catchability coefficient. Expression (1) states that net expansion of the stock occurs due to growth $F(.)$at the current period less the harvest rate. It is assumed that $\frac{\partial F}{\partial C} > 0$ (for stock levels less than the one associated with Maximum Sustainable Yield), $\frac{\partial F}{\partial S} \geq 0$.

The logistic growth function will be adopted in a manner similar to that described by Foley *et al.*[23] We assume that SAV can influence both the intrinsic growth rate (r) and carrying capacity (K) of the stock in the following way (Foley *et al.*[23] argue that the habitat can affect the intrinsic growth rate, resulting in the term $rK(S)$to appear in the logistic growth function):

$$F\left(C,S\right) = rK\left(S\right)C\left(1 - \frac{C}{K\left(S\right)}\right) \tag{2}$$

The following relationship between SAV and the intrinsic growth rate and carrying capacity for crabs is assumed:

$$K\left(S\right) = K + \mu S \tag{2'}$$

This functional form is flexible and allows for three different situations. First, if SAV is facultative for crabs, then $K > 0$ and $\mu > 0$. In this case, the facultative role of SAV is clear. For $S = 0$, the species is not driven to extinction, but rather would have a carrying capacity of K. The coefficient μ captures the effect of SAV on the intrinsic growth rate and carrying capacity of blue crabs. If $K = 0$ and $\mu > 0$, then $K\left(S\right) = \mu S$, and SAV is an essential habitat because for $S = 0$ the stock is driven to extinction. Finally, another theoretical possibility is that $\mu = 0$, in which case SAV does not matter to blue crabs in the Bay (of course that would be against studies based on laboratory experiment[8] and other studies[10] that have shown a positive association between SAV and blue crabs in the Bay. We chose to include this possibility and let our data indicate whether SAV matters for crabs). Given the functional form given by $(2')$, the logistic growth function now becomes

$$F\left(C,S\right) = rC\left(K + \mu S\right)\left(1 - \frac{C}{K + \mu S}\right) \tag{2''}$$

Substituting the Schaefer production function and expression $(2'')$ into (1) and simplifying, we get:

$$\dot{C} = \left[r\left(K + \mu S - C\right) - qE\right]C \tag{3}$$

Given that the blue crab industry has the characteristics of open-access fishery, assuming that blue crab watermen are price-takers, and letting p and v be the price per crab and unit cost of effort respectively, dissipation of economic rents implies:

$$pqEC = vE \tag{4}$$

The bionomic open-access equilibrium level of crab stock C, assuming non-zero unit cost of effort and price, is calculated from expression (4) as

$$C = \frac{v}{pq} \tag{5}$$

In addition, we assume that $\frac{v}{pq} < K(S)$. Setting $\dot{C} = 0$ in (3) we have

$$E = \frac{r\left[\left(K + \mu S\right) - C\right]}{q}\ for\ \dot{C} = 0 \tag{6}$$

Solving (6) for C we get

$$C = \left(K + \mu S\right) - \frac{Eq}{r} \tag{7}$$

Substituting (7) into the production function and rearranging yields

$$h = qKE + q\mu ES - \frac{q^2E^2}{r} \tag{8}$$

Now, setting $d_1 = qK$, $d_2 = q\mu$ and $d_3 = -\frac{q^2}{r}$ expression (8) becomes

$$h = d_1E + d_2ES + d_3E^2 \tag{9}$$

We refer to Equation (9) as the facultative habitat model. Equation (9) nests the sub cases of SAV as essential habitat or irrelevant habitat. For $d_1 = 0$ and $d_2 > 0$, we have that $qK = 0$ and because $q > 0$ (it would not make any sense to set $q = 0$ because that would imply zero harvest), this would imply that $K = 0$. Therefore, estimating the facultative habitat model and testing whether d_1 is statistically different from zero would answer whether SAV seems to be a facultative or essential habitat. An alternative test would be to examine whether SAV matters or not for crabs in the Bay – *i.e.*, test whether d_2 is statistically different from zero (again, $d_2 = q\mu$ and because $q > 0$, $d_2 = 0$ would necessarily imply that $\mu = 0$). Barbier and Strand[24] assumed that mangrove is essential habitat for shrimps, imposing *a priori* $d_1 = 0$ or $K = 0$. If $K$is, in fact, nonzero, that assumption would lead to a biased estimate of μ.

The next step is to compute comparative static effects in equilibrium, triggered by SAV changes. The impacts of SAV changes on the blue crab fishery are calculated based on the assumption that the open-access equilibrium described by equations (5) and (6) is stable and that fishing effort adjusts instantaneously to reach a new equilibrium. Like Barbier and Strand[24] and Foley *et al.*[23], we will not consider the case where a change in SAV makes the steady-state equilibrium infeasible by causing the fishery to switch to a different path (Barbier and Strand showed that we can have only two trajectories, assuming an initial level of stock. The first one is a stable spiral that leads to the open access equilibrium. The second leads the stock to a rapid decline reducing it to near-extinction levels. As the authors argued, such a case can exist if the initial level of effort is too high given the initial stock condition[24]. There is no evidence that the Bay's blue crab fishery has been close to collapse, and therefore considering that only the first type of equilibrium is attained with changes in SAV is a reasonable assumption). Equation (6) of the steady-state open access equilibrium is rewritten here as

$$E^{*}=\frac{r\left[(K+\mu S)-C^{*}\right]}{q} \tag{10}$$

where the symbol * indicates that the fishery is in steady state. From (10), the comparative static effect from a change in SAV on the equilibrium level of fishing effort can be calculated.

$$\frac{dE^{*}}{dS}=\frac{r\mu}{q} \tag{11}$$

Using (11) and (5), the effect on the equilibrium harvest level (denoted by h^{*}) can be explicitly found to be

$$dh^{*}=qC^{*}dE^{*}=r\mu C^{*}dS=\frac{r\mu v}{pq}dS \tag{12}$$

The change in fishery revenue is given as

$$pdh^{*}=\frac{r\mu v}{q}dS \tag{13}$$

The impact of a change in SAV on effort, harvest and revenues depends on the bioeconomic parameters r, μ, v, q and p. However, we do not need to know all of them in order to calculate the impacts from changes in SAV. From the estimated equation (9) we have recovered $d_2 = q\mu$ and $d_3 = -\frac{q^2}{r}$, and expressions (12) and (13) can be rewritten as

$$dh^{*}=\frac{r\mu v}{pq}dS=-\frac{vd_2}{pd_3}dS \tag{14}$$

$$pdh^{*}=-\frac{vd_2}{d_3}dS \tag{15}$$

Therefore, in order to calculate the impacts from changes in SAV, we require only values of v and p. Given that the underlying assumption for estimating (9) is that the fishery is in open-access equilibrium, we know that rents dissipate, or $ph = vE$. Already having data on harvest and effort (Data on harvest and effort are essential for the estimation of equation (9)), all we need are time-series data for price for the period 1993-2011 (As will be discussed in the following sections, this will end up being the time period for the analysis). in order to recover v.

There are two alternative ways to test whether SAV matters for crab stock and to estimate the comparative static effects of SAV on equilibrium, effort and harvest. Using equilibrium conditions (5) and (6), the Schaefer production function becomes

$$\begin{aligned} h=qCE=q\frac{v}{pq}E&=\frac{v}{p}\left[\frac{r\left(K-v/pq\right)}{q}+\frac{r\mu}{q}S\right] \\ &=\frac{v}{p}\left[\frac{r\left(K-v/pq\right)}{q}\right]+\frac{vr\mu}{pq}S \end{aligned}$$

and for $b_0=\frac{v}{p}\left[\frac{r(K-v/pq)}{q}\right]$ and $b_1=\frac{vr\mu}{pq}$ we have

$$h=b_0+b_1S \tag{16}$$

Expression (16) is an estimable equation that can provide an alternative way to test whether the habitat matters for the species. Notice that a statistical test of whether $b_1 = 0$ also tests whether $\mu = 0$, since $v,\ r,\ q$ and p are all assumed positive. This alternative test, to our knowledge, has never been used. Moreover, the comparative static effects in equilibrium from SAV changes yield

$$dh^{*}=b_1dS=\frac{vr\mu}{pq}dS$$

$$pdh^{*}=\frac{vr\mu}{q}dS$$

which are identical to the ones described by expressions (12) and (13).

The second alternative is to use expression (10) and replace C with its bionomic open access equilibrium level to obtain upon rearrangement

$$E=\frac{r\left(K-v/pq\right)}{q}+\frac{r\mu}{q}S$$

For $a_0=\frac{r(K-v/pq)}{q}$ and $a_1=\frac{r\mu}{q}$ we have

$$E=a_0+a_1S \tag{17}$$

Expression (17) is another estimable equation that can provide the second alternative way to test whether the habitat matters for the species, with $a_1 = 0$ also testing whether $\mu = 0$.

2.2 Data description

For the estimation of equation (9), data for aggregate SAV, effort and harvest are required. Annual Bay-wide SAV coverage area in hectares was obtained from the Virginia Institute of Marine Sciences[14] for the years 1984-2011. Data for aggregate fishing effort and harvest were available for the three regions of the Bay where blue crab harvest takes place: Potomac River, Virginia and Maryland. The goal was to add fishing effort across the three regions, as well as the corresponding harvest, in order to obtain aggregate (Bay-wide) effort and harvest. Starting with the Potomac River, annual effort data were provided by the Potomac River Fisheries Commission[27] for the years 1986-2011 and included the number of hard pots fished and the associated harvest in pounds. For the Virginia portion of the Bay, annual effort data were provided by the Virginia Marine Resources Commission[28] for the years 1993-2011. The data contained information on average annual number of pots, as well as the count of pots that contributed to that average. Total number of hard pots for every year was calculated by multiplying these two figures. The data also included harvest of crabs in pounds caught by hard pots. The 2012 Cap Log Report for Virginia[29] indicated that almost all harvest in 2010 in Virginia (99%) resulted from catch using hard pots.

Effort data for Maryland were provided by the Fisheries Administration of the Maryland Department of Natural Resources[15]. The data covered the months of March to December for the period 1992-2011 and included several gear types, such as hard pots, peeler pots, trotlines, net rings, collapsible traps, scrapes, dip nets and the like, along with their associated harvest in pounds. In addition, the data included gear numbers, gear hours, and hours and days fished, but we chose to use gear numbers only, in order to be compatible with data for the other two regions. The 2011 Cap Log Report for Maryland[30] indicated that as of 2007, 97% of the total harvest had been made using hard pots and trotlines, with 66% of that harvest attributed to pots and 31% to trotlines. After we converted the monthly harvest from pots and trotlines into annual figures in our sample, we were able to validate this information. Having annual figures for hard pots and trotlines for the period 1993-2011, we needed to know the equivalence between the two types of gear in order to estimate the aggregate amount of effort in Maryland that would be comparable to the measures of effort for the Potomac and Virginia achieved using pots. For each year, the catch-per-unit effort (CPUE) for both pots and trotlines in Maryland was calculated along with the ratio of $CPUE_{pots}$ to $CPUE_{trotlines}$. This ratio was multiplied by the number of trotlines, allowing conversion of trotline effort into pot effort for each year in the sample, as well as calculation of the total number of pots for Maryland. Adding the corresponding harvest of the two gear types was straightforward.

For the comparative static effects described by equations (14) and (15), we needed additional information about price per pound and unit cost of fishing effort. Blue crab landings (in pounds) and dockside values data for both Maryland and Virginia were available from the National Oceanic and Atmosperic Administration (NOAA) Fisheries Office of Science and Technology[26]. From these, price per pound for both states and the average price in the Bay were calculated for every year. Next, using the zero-rent condition, the unit cost of effort was recovered as $v = \frac{ph}{E}$ for every year in our sample. The final data set is available in the Table 1.

3 Empirical results

3.1 The role of SAV as essential habitat for blue crabs

Aggregating the data for harvest and effort (As section 4 indicates, SAV data included Bay-wide observations) across the three regions resulted in a sample of 19 observations for the time period 1993-2011. Table 2 below presents the summary statistics for the pooled sample.

Our first step was to replicate the results of Barbier and Strand[24] using their model that assumes habitat is essential. We dropped the term $d_1 E$from expression (9), assuming that $K = 0$, and ran three OLS regressions: with SAV in contemporaneous time, with SAV lagged one year, and with SAV lagged two years (Even though our data for harvest and effort (number of pots) were limited only for the period 1993-2011, the fact that SAV data were available from 1984 enabled us to create such a lag without reducing the sample size). Lagging SAV for up to two years seems reasonable given the life cycle of the species. In particular, crabs hatch in the ocean where they feed with phytoplankton. About 45 days later, juvenile blue crabs (known as *megalopae*) are transported by currents, tides and their own movements back into the Bay. The juvenile blue crabs will utilize seagrass and other types of SAV as sources of food, habitat and shelter against predation for about 14 to 18 months before becoming adults[31]. Thus, there is about a 15- to 19-month lag between the time crabs hatch and the time they are recruited into the adult stock. Regression results are presented in Table 3 below.

In all specifications, results indicated that SAV is an important habitat for blue crabs in the Bay. The highly statistically significant coefficient of the interaction term between effort and SAV implied that $\mu > 0$ in the expression $K(S) = \mu S$. Furthermore, the coefficient of effort squared had the expected sign of diminishing marginal productivity. Both models with lagged SAV better explained the variation in harvest ($R^2 = 0.90$ as opposed to 0.88), and gave more significant coefficients for squared effort. The model with two years lagged SAV,

Table 1. Data Appendix

Year	SAV	SAV1	SAV2	SAV3	Number of Pots	Harvest (pounds)	Av. Price ($/lbs)	Unit cost effort (v)
1993	29587	28591	25623	24296	104736742.6	86501178	0.57	0.47
1994	26484	29587	28591	25623	95044784.42	64360205	0.70	0.47
1995	24251	26484	29587	28591	114109204.3	58970180	0.76	0.39
1996	25696	24251	26484	29587	90894910.51	54649386	0.66	0.39
1997	28032	25696	24251	26484	116951727	63980596	0.74	0.41
1998	25704	28032	25696	24251	126438647.1	44989326	0.81	0.29
1999	26190	25704	28032	25696	109430544	49961582.71	0.82	0.37
2000	27986	26190	25704	28032	110236486	35071426.3	0.90	0.29
2001	31520	27986	26190	25704	109173360	34925753	0.90	0.29
2002	36283	31520	27986	26190	104604991.5	36679665	0.80	0.28
2003	24966	36283	31520	27986	128627721.2	36213218	0.87	0.25
2004	29519	24966	36283	31520	90524078.93	45713902.13	0.85	0.43
2005	31671	29519	24966	36283	88454235.96	45022292.65	0.86	0.44
2006	23941	31671	29519	24966	84434915.88	41642314	0.73	0.36
2007	26271	23941	31671	29519	117796529.9	34807375.28	0.97	0.29
2008	31104	26271	23941	31671	144665733.8	51148669.12	1.08	0.38
2009	34768	31104	26271	23941	199328725.3	54687769.95	0.97	0.27
2010	32243	34768	31104	26271	223247449.8	74044303.31	0.96	0.32
2011	23457	32243	34768	31104	175411919.1	64225462.81	0.91	0.33

Table 2. Summary statistics

Variable	Obs	Mean	Std. Dev	Min	Max
Harvest (lbs)	19	51,500,000	14,500,000	34,800,000	86,500,000
Effort (# of pots)	19	123,000,000	38,000,000	84,400,000	223,000,000
SAV (hect)	19	28,403.84	3,720.553	23,457	36,283

however, yielded a coefficient of squared effort more statistically significant compared to its one-year-lag counterpart. Therefore, the comparative static analysis was conducted based on the model containing two-year lagged SAV.

The comparative static effects for the Bay were performed using expressions (14) and (15). The results for every year in our sample are presented in Table 4.

On average, over the 1993-2011 period, a marginal change in SAV (1 hectare) yielded a change of 6,749 pounds in blue crab harvest. In terms of revenues, the average figure from a marginal change in SAV was $5,409. During the period 1993-2011, the Bay experienced an average annual loss of 340.55 hectares. This translated into losses of approximately 2.3 million pounds in harvest and $1.84 million in revenues. However, it proved more useful to calculate the fishery welfare impacts from observed SAV changes, relative to exogenously specified SAV-restoration goals. In 2003, the Chesapeake Bay Program implemented the so-called *Strategy to Accelerate*

Table 4. Comparative static effects estimates from marginal (1 hectare) changes in SAV

Year	Av. Price ($/lbs)	Unit cost effort(v)	Change in equilibrium harvest (lbs)	Change in equilibrium revenues ($)
1993	0.57	0.47	12,639	7,191
1994	0.70	0.47	10,363	7,246
1995	0.76	0.39	7,908	6,018
1996	0.66	0.39	9,201	6,028
1997	0.74	0.41	8,372	6,236
1998	0.81	0.29	5,445	4,407
1999	0.82	0.37	6,987	5,726
2000	0.90	0.29	4,869	4,376
2001	0.90	0.29	4,896	4,389
2002	0.80	0.28	5,366	4,291
2003	0.87	0.25	4,308	3,750
2004	0.85	0.43	7,728	6,602
2005	0.86	0.44	7,789	6,690
2006	0.73	0.36	7,547	5,519
2007	0.97	0.29	4,522	4,376
2008	1.08	0.38	5,411	5,868
2009	0.97	0.27	4,199	4,081
2010	0.96	0.32	5,076	4,893
2011	0.91	0.33	5,603	5,084
Mean	0.83	0.35	6,749	5,409

Table 3. Regression results with SAV assumed to be essential habitat

Dep. Variable: harvest	OLS (SAV_t)	OLS (SAV_{t-1})	OLS (SAV_{t-2})
Efforts* SAV(ES)	0.0000206***	0.0000239***	0.0000202***
	(4.44 e-06)	(5.16 e-06)	(3.04 e-06)
Effort squared (E^2)	-1.47e-09+	-2.22e-09*	-1.32e-09**
	(8.17 e-10)	(8.50 e-10)	(4.27 e-10)
N	19	19	19
R^2	0.88	0.90	0.90

Note: $+p < 0.10$, $^* p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$; robust standard errors are given in parentheses

Table 5. Regression results with SAV not assumed to be essential habitat

Dep. Variable: harvest	OLS (SAV_t)	OLS (SAV_{t-1})	OLS (SAV_{t-2})
Effort (E)	0.673***	0.626*	0.633**
	(0.135)	(0.229)	(0.190)
Efforts* SAV(ES)	-2.25e-06	-2.82e-07	-5.13e-07
	(4.92e-06)	(0.00001)	(5.69 e-06)
Effort squared (E^2)	-1.44e-09*	-1.50e-09+	-1.51e-09**
	(5.59e-10)	(7.78 e-10)	(5.03 e-10)
N	19	19	19
R^2	0.93	0.93	0.93

Note: +$p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; robust standard errors are given in parentheses

the Protection and Restoration of Submerged Aquatic Vegetation in the Chesapeake Bay, suggesting a Bay-wide SAV restoration goal of 185,000 acres[10], or approximately 74,866 hectares. The difference between this goal and the latest SAV observation in our sample (23,457 hectares in 2011) equaled 51,409 hectares. If current restoration efforts will achieve the Chesapeake Bay Program's goal, the fishery welfare implication would be approximate changes of 347 million pounds in equilibrium harvest and $278 million in equilibrium revenues. Like Barbier and Strand[24], our results to this point indicated that habitat change results in large impacts on fisheries productivity in the system.

3.2 The role of SAV as facultative habitat for blue crabs

Our second step was to run the more general model, shown by equation (9). The results are presented in Table 5.

All regressions explained equally well the variation in harvest ($R^2 = 0.93$), and the estimated coefficient of squared effort had the expected sign. However, in all specifications we rejected the null hypothesis that $d_1 = 0$. That means that $K > 0$ in the expression $K(S) = K + \mu S$,indicating that SAV is not essential habitat. Moreover, in all specifications the coefficient of the interaction between effort and SAV was found to be statistically insignificant. Given these results, we failed to reject the null hypothesis that $d_2 = 0$ and $\mu = 0$. This finding implies that SAV does not matter for blue crabs in the Bay, contradicting our previous results that were based on an *a priori* assumption, similar to that of Barbier and Strand[24], that SAV is essential habitat. When we used the more restrictive essential model, we found that more SAV promotes the carrying of the species, but when using the more general model, this notion could not be supported.

Our results indicate that assuming *a priori* that $K = 0$ and running the essential-habitat model without the term $d_1 E$in expression (3.9) leads to potential model misspecification. If the true relationship between stock and its habitat is essential, then dropping the term $d_1 E$creates no issues. However, if the true relationship supports the facultative-habitat model with $K > 0$, a model misspecification occurs and the estimated coefficient of the interaction term between effort and habitat (d_2) will be biased. Model misspecification also will generate a biased estimate of the coefficient of squared effort. We were not able to calculate comparative static effects from the more general model suggested by Foley[23], because, in all specifications, both coefficients of $E * S$and squared effort (d_2 and d_3) were found to be negative, making it counterintuitive to calculate the change in harvest and revenues from observed SAV changes (In expression (14) we have $dh^* = -\frac{vd_2}{pd_3} dS$. If both d_2 and d_3 were negative, d$\frac{h^*}{dS} would\ be < 0$, which would imply that SAV is actually detrimental to the crab stock).

To further test whether SAV matters for the crab stock, we also used our alternative approach of regressing harvest on SAV, including a constant as described by equation (16) in section 3. The results are illustrated in Table 6.

All specifications of SAV explain very poorly the variation in harvest (R^2). However, in all cases, the null hypothesis (that the coefficient of SAV in (16) is zero and thus $\mu = 0$) could not be rejected, indicating that SAV does not matter as habitat for crabs. Therefore, our simplified approach was able to confirm our previous results from the general facultative-habitat model. Only the specification with one-year lags gave the expected positive sign, indicating that a marginal change in SAV (1 hectare) is associated with 450.8 pounds of harvest. Given the insignificant coefficient of SAV, no comparative statics were calculated. Table 7 presents the results of the second alternative approach we used to test whether SAV matters, where effort is regressed on SAV.

The variation in harvest (R^2) was poorly explained by the specifications of SAV in contemporaneous time and in the two-year lag. Similar to our first alternative approach, the null hypothesis (that the coefficient of SAV in (16) is zero and thus $\mu = 0$) could not be rejected, indicating that SAV does not matter as habitat for crabs. We were able to reject the null hypothesis that the habitat does not

Table 6. Regression results from regressing harvest on SAV (alternative approach)

Dep. Variable: harvest	OLS (SAV_t)	OLS (SAV_{t-1})	OLS (SAV_{t-2})
SAV(S)	-82.55	450.79	-176.70
	(819.81)	(1046.77)	(895.18)
Constant	5.38e+07*	3.85e+07	5.65e+07*
	(2.28e+07)	(2.92e+07)	(2.59e+07)
N	19	19	19
R^2	0.0004	0.0120	0.0018

Note: +$p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; robust standard errors are given in parentheses

Table 7. Regression results from regressing effort on SAV (alternative approach)

Dep. Variable: effort	OLS (SAV_t)	OLS (SAV_{t-1})	OLS (SAV_{t-2})
SAV(S)	2732.62	5180.03+	1632.39
	(3054.19)	(2749.57)	(2817.23)
Constant	4.52e+07	-2.57e+07	7.66e+07
	(8.35e+07)	(7.33e+07)	(7.70 e+07)
N	19	19	19
R^2	0.0715	0.2302	0.0223

Note: +$p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; robust standard errors are given in parentheses

matter for the crab stock only at a 10% confidence level in the specification with one-year lags.

Barbier and Strand[24] assumed *a priori* that mangrove was an essential habitat for shrimps in Campeche, Mexico. That they obtained a significantly positive coefficient of the interaction term between effort and habitat is therefore not surprising. Even though such modeling decisions come after studying species biology and their habitat association or after consulting with ecologists, whether a specific habitat is essential or facultative is ultimately an empirical question. This is so because the essential-versus-facultative debate sheds light on the question of how a species would behave in complete absence of its habitat. For this reason, Foley *et al*.[23] discussed the importance of empirically determining habitat-fishery linkages. We point out that the estimated model by Barbier and Strand might be flawed and argue in favor of the more general facultative model that nests its essential counterpart. To the extent that SAV is truly an essential habitat for Chesapeake Bay crabs, our comparative static results are plausible and valid. Nonetheless, with our data, we cannot empirically support whether SAV is an essential or facultative habitat.

4 Discussion and policy implications

Following the methodology described by Foley *et al*.[23], we estimated an empirical bioeconomic model that could test whether SAV is an essential or facultative habitat for blue crabs in the Chesapeake Bay. Our results show that, if we do not have perfect information on habitat-fisheries linkages, the right approach would be to estimate the more general facultative-habitat model that incorporates the essential-habitat model as a subcase. Failure to do so can result in model misspecification and biased estimates.

Using a sample of 19 observations, we first ran the essential-habitat model assumed in Barbier and Strand[24]. This model suggested that SAV has a strong positive impact for crabs. The comparative static analysis based on the essential-habitat model showed that a marginal change in SAV yields a change of 6,749 pounds in harvest and $5,409 in revenues. With an average Bay-wide annual loss of 340.55 hectares between 1993-2011, these findings would suggest approximately 2.3 million pounds were lost in harvest and $1.84 million in revenues. If current restoration efforts will achieve the Chesapeake Bay Program's goal of 74,866 hectares of SAV, our estimation approach predicts welfare changes of approximately 347 million pounds in equilibrium harvest and $278 million in equilibrium revenues.

However, our comparative static estimates are likely to be overstated if SAV is not truly an essential habitat, and we argue that this might be the case for the results in Barbier and Strand[24] as well. When we ran the more general facultative-habitat model, we found that habitat does not matter for the species, contradicting our previous results. In addition, we were able to confirm this assertion using our two alternative approaches (at 5% confidence level), which we showed are also valid tests of whether SAV matters. Although there is some scientific evidence [8,9] to support the notion that SAV should at least be a facultative habitat, with the data at hand, we cannot empirically support that SAV is either an essential or facultative habitat for the species.

This paper is not free of caveats and we mention the most important here. To begin with, a big assumption is that the open-access equilibrium is reached quickly and at every single period. Year-to-year changes in SAV trigger changes in the stock, which is harvested to its bionomic level fast enough so there is no excess stock for the next season. However, fixed costs involved in fishing capacity would make it hard for fishermen to rapidly adjust to stock changes on a yearly basis. The assumption that our data satisfy the open-access rent dissipating condition at all times is therefore a strong one. Smith[32] classified models like the one in this paper as *equilibrium bioeconometric models,* where, through estimation, the researcher may recover economic parameters, biological parameters or both. Such models differ from other bioeconomic models[33] where results are obtained via simulations. On the other hand in equilibrium bioeconomentric models, since data points are snapshots of nullclines, system dynamics are not well understood[32]. Such dynamics, from both ecological and economic points of view, are absent from this paper as well.

Another caveat is the simplistic way we added trotlines to pots in order to create an aggregate level of effort for Maryland. A large number of variables, other than the simple catch-per-unit-effort adopted here, are involved in gear equivalency[34]. Most importantly the two gears are almost never used in the same area, with pots being used in the mainstream regions of the Bay and trotlines in rivers. This fact, along with unobservable (The word "unobservable" here refers to the analyst because data about the number of runs a trotline-crabber makes in a day are not available and very difficult to get[34]) actions of fishermen, such as the number of runs a trotline-crabber makes in a day (which would be his/her total effort), make a precise gear conversion extremely hard.

Lastly, the number of observations in our data set is rather limited. There may also be issues with data quality. Regarding the small sample size, a longer time series would probably provide more reliable estimates. Smith[32] pointed out that time series data for studies like ours are very limited. As for the quality of our data, it is likely that effort and the associated harvest in Maryland and Virginia are under- or over-reported in logbooks from which the data are taken[28,35]. As more and/or better data become available in the future, we plan to re-estimate our model and address the above limitations.

Conflicts of interest

The authors declare no conflict of interest.

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