Evaluating habitat-fishery interactions: The case of Submerged Aquatic Vegetation and Blue Crab fishery in the Chesapeake Bay

Nikolaos Mykoniatis
Department of Agricultural Economics, Sociology and Education
The Pennsylvania State University

Richard Ready
Department of Agricultural Economics, Sociology and Education
The Pennsylvania State University

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 nests the essential-habitat model into its facultative-habitat counterpart is estimated. Two alternative approaches are used to test whether SAV matters for the crab stock. Our results indicate that, if we do not have perfect information on habitat-fisheries linkages, the right approach would be to run the more general facultative-habitat model instead of the essential-habitat one. Failure to do so can result in model misspecification and upward-biased estimates of the impact of habitat on species productivity. With our data we fail to reject the null hypothesis that SAV is irrelevant for crabs in the Bay.

1. Motivation and Research question

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 (Kahn and Kemp, 1985). This type of vegetation plays a vital role, since it provides habitat and sources of food for many species including waterfowl, fish and invertebrates (Lubbers et al., 1990; Heck et al., 1995). For the Bay, SAV is considered one of its main health indicators and annual monitoring and restoration activities take place (VIMS).

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 an ecological and commercial point of view. Ecologically they are a vital food-web link in the ecosystem because they are major predators of benthic communities, while prey for many fish species (NOAA, Chesapeake Bay Office). 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 (NOAA, Chesapeake Bay Office) with more than $100 million in dock value (NOAA Fisheries, Office of Science and Technology). The species can be harvested throughout the Bay with males being in the mesohaline and oligohaline[1] portion of the estuary in Maryland and upper tributaries, while females prefer saltier waters in the mainstem and Virginia (NOAA, Chesapeake Bay Office). Crabs are harvested in the Chesapeake Bay using a variety of gear. Pots are by far the most common harvesting technique in Virginia (Miller, 2001). Other methods such as trotlines[2], handline, dipnet, dredge and the like are also used in Maryland and the Potomac (NOAA, Chesapeake Bay Office).

SAV is thought to be utilized by blue crabs as source of food, nursery grounds for juveniles, as well as shelter during mating and molting. Field and laboratory experiments indicate that juvenile blue crabs grow substantially more when SAV is present than when it is not (Perkings-Visser et al., 1996). In particular, as many as thirty times more young crabs have been counted in SAV, such as eelgrass, than on bare bottom (CBF 2007, cited in CBF Report, 2008).

---

[1] Mesohaline and oligohaline refer to medium and low salinity zones respectively.
[2] As will be discussed in section 4, trotlines and pots are the most common fishing techniques in Maryland.

However, SAV in the Bay experienced a big decline between 1960 and the mid 1980's (Kahn and Kemp, 1985), with more than half of the SAV to disappear from Bay's waters (U.S. Fish and Wildlife Service, Chesapeake Bay Field Office). That loss has been primarily attributed to poor water quality (Kemp et al., 1983, cited in Kahn and Kemp, 1985). In particular, nutrients trigger algal growth, both in the water and upon SAV, preventing sun light to reach the plant resulting in reduced growth and eventually leading to death.

Plotting blue crab abundance and harvest over the last twenty two years one can observe that both stock and harvest have a downward trend. In particular stock and harvest have experienced a big decline during the 90s 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)
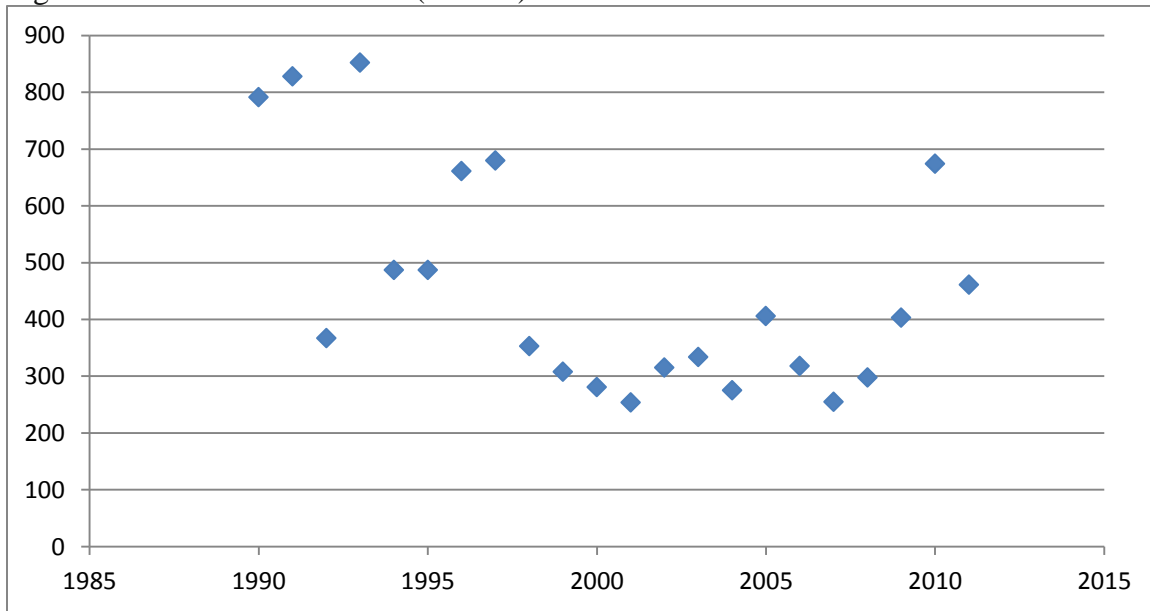
Source: NOAA Chesapeake Bay Office, Winter Dredge Survey

Figure 2: Bay-wide blue Crab harvest (pounds)
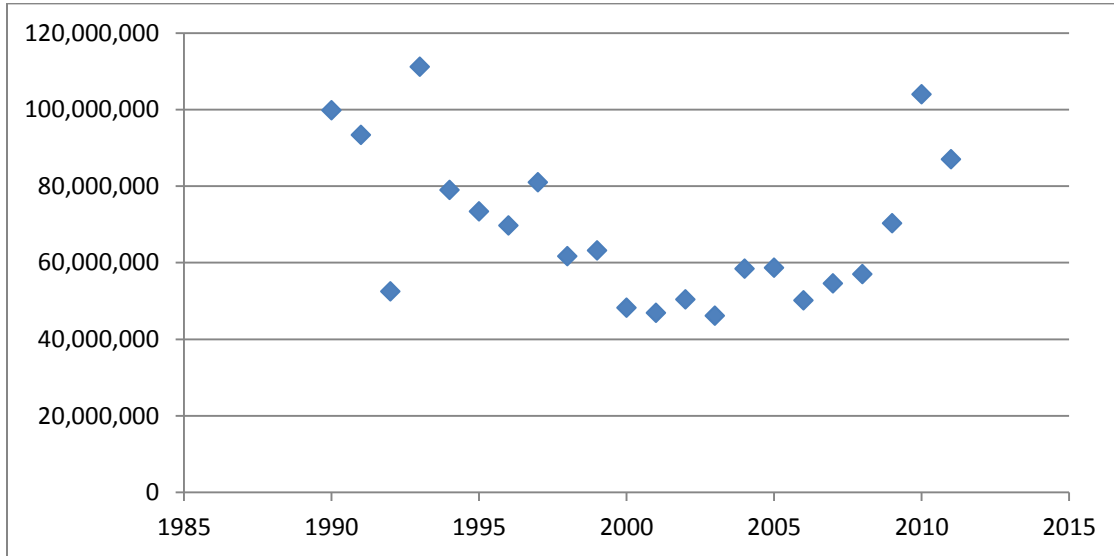
Source: NOAA: Office of Science and Technology

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

Figure 3: Bay-wide SAV coverage (hectares)

Source: VIMS SAV program

Nonetheless, the SAV pattern over the last 22 years can be characterized as fluctuating, rather decreasing and generally does not have the same peaks and valleys as the stock. Examination of the SAV data taken from VIMS reveals that during the period 1990-2011 the Bay has experienced an average annual loss of about 40 hectares. The fact that SAV and blue crab stock do not follow exactly the same pattern, is not an indicator that SAV does not play an important role for the species, as tides, wate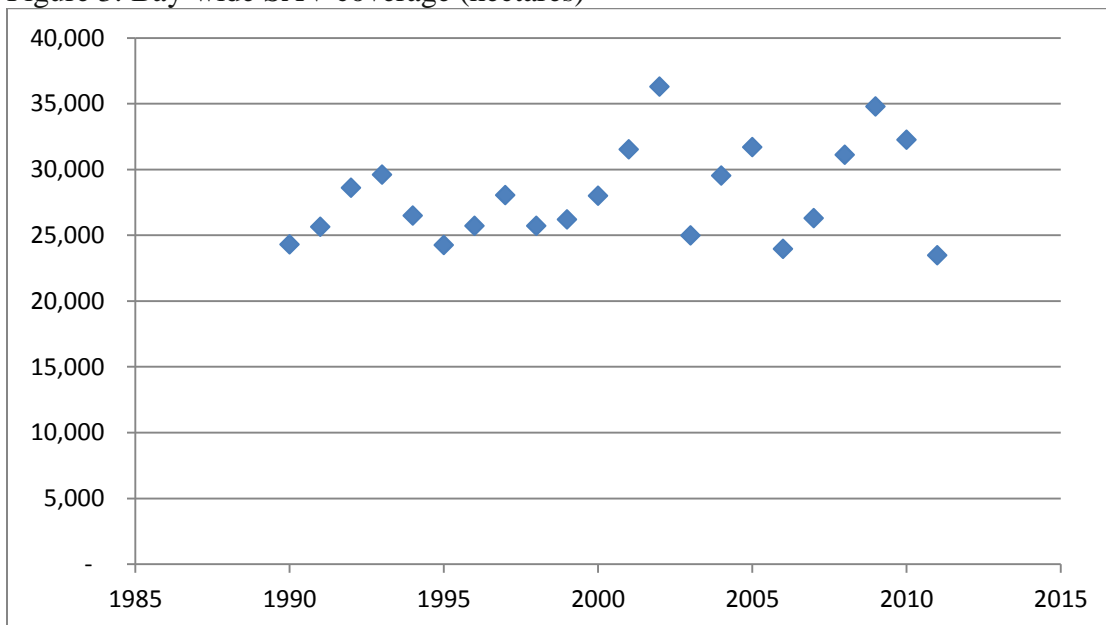r currents, water temperature, changes in salinity due to irregular precipitation and other stochastic processes may also be responsible for fluctuations in blue crab's dynamics (EBFM Blue Crab Species Team Summary p.2). The species has a tight link with environmental factors other than SAV. These environmental factors are being affected by global climate change, the exact effect of which on species' recruitment is largely unexplored (EBFM Blue Crab Species Team Summary).

Given the importance of SAV and crabs for the Bay and their downward trend, the research questions that emerge from the above discussion can be summarized as follows: 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. (2012) classify the modeling approaches by the way 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 species' extinction if the habitat is completely eliminated (Foley et al., 2012). In contrast, if the habitat is essential, then the species cannot survive without at least some of the habitat. There is a third possibility that Foley et al. did not consider. Namely, 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 the first part of our research question interesting and important. If SAV will be found to be essential, that would be a valuable piece of information to environmental managers and policy makers making the protection and restoration of SAV of paramount importance.

Turning to the second research question, our objective is to quantify the productivity changes in the blue crab fishery triggered by changes in SAV. In particular, we will quantify to what extend changes in SAV affect fishing effort, harvest and revenues in equilibrium. This paper will address the following points:

- Develop an empirical bioeconomic model crabs under the assumption of open access. This model will be general with regards to the role that SAV has for blue crabs. Statistical tests will be conducted to determine whether SAV is essential habitat, facultative habitat, or irrelevant for crabs.
- Comparative static effects in equilibrium of changes in harvest, effort and revenues triggered by SAV changes will be calculated.

2. Literature Review

The empirical bioeconomic literature reviewed here contains two stands of literature: one that assumes that the 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 (1981) quantify the effect of marsh area of Florida's Gulf Coast on the economic productivity of blue crabs. Their main finding is 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 (1985) estimate the lower bound of a damage function related to losses in SAV. Their analysis is related to shelter SAV provides to striped bass. Welfare changes are measured in terms of producer and consumer surplus. The work by Anderson (1989) is similar to Kahn and Kemp but the author deals with the other side of the coin, quantifying the economic benefits related to the restoration of blue crab's preferred habitat in Virginia's portion of the Bay. The preferred habitat is however narrowed down to be the seagrass. The net benefit is found to be $1.8 and $2.4 million per year for producers (fishermen) and consumers respectively (Anderson, 1989). The results were obtained through simulation instead via direct estimation.

Some authors have acknowledged the importance of wetland, as habitat for blue crabs at the Gulf Coast (Ellis and Fisher, 1987). They analyzed how the increase of wetland impacts the species and value this change with changes in producer and consumer surplus. A big assumption is that the resource is sole-owned. Later on, Freeman (1991) addresses the same topic and

application under two alternative management regimes, namely sole ownership and open access. It is shown that the marginal value of the resource will not always be lower under open access compared to its counterpart from sole ownership (Freeman, 1991). In both papers stock is a function of habitat.

Studies related to fisheries-habitat interactions that test whether and to what degree habitat matters are, to our knowledge, few. Swallow (1994) indirectly tested the importance of habitat by formulating two resource sectors, one renewable (fishery) and one non-renewable (land development). The non-renewable resource applies to the drainage of wetland near coastal areas, which affects brown shrimp productivity through changes in water salinity. The stock is taken to be affected only through its habitat, which deteriorates by irreversible land development (drainage of wetland). The important trade-off between preservation and development of wetlands is then empirically examined (Swallow, 1994). Of particular relevance to this paper is the recent study by Foley and colleagues (2010). By applying the production function approach, the authors estimate 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 habitat and one with facultative and demonstrated that the essential one fits the data better (Foley et al., 2010). Moreover, the authors estimated annual losses in harvest associated with different scenarios of habitat degradation, due to lack of habitat data.

In their important contribution, Barbier and Strand (1998) address the impact of mangrove systems as essential habitat (breeding and nursery grounds) for shrimps in Campeche, Mexico. The authors develop an open-access fishery model, where mangrove area is assumed to enhance the carrying capacity of the stock and therefore production and value of harvest in the fishery (Barbier and Strand, 1998). Later on, Barbier and et al. (2002) 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 treats habitat as being essential, assuming a positive spillover of mangroves on species' carrying capacity. Others (Sathirathai and Barbier, 2001) adopt the same approach for Southern Thailand, while others (Lynne et al., 1981) incorporate lagged effects on their approach.

3. A habitat-fisheries interaction model

Our model is based on Barbier and Strand (1998) and Foley et al. (2010). We begin with blue crab stock dynamics. With E_t and S_t being the fishing effort and SAV respectively, the equation of motion for the crab stock (C) can be expressed in a standard manner as

$$\dot{C}_t = F(C_t, S_t) - h(C_t, E_t) \qquad (1)$$

where $h(.)$ stands for harvest as a function of the crab stock and the amount of fishing effort. The Schaefer production function is $h(C_t, E_t) = qE_tC_t$ with q being the constant catchability coefficient. Expression (1) states that net expansion of the stock occurs due to growth at the current period less the harvest rate. It is assumed that $\frac{\partial F}{\partial C_t} > 0$[3], $\frac{\partial F}{\partial S_t} \geq 0$.

The logistic growth function will be adopted in a manner similar to Foley et al. (2010). We assume that SAV can influence both the intrinsic growth rate and carrying capacity of the stock in the following way[4]:

$$F(C_t, S_t) = rK(S_t)C_t \left(1 - \frac{C_t}{K(S_t)}\right) \qquad (2)$$

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

$$K(S_t) = K + \mu S_t \qquad (2')$$

This functional form is flexible, and allows for three different situations. First, if SAV is facultative for crabs, then K>0 and μ>0. In this case, the facultative role of SAV is clear. For $S_t = 0$ 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.

---

[3] For stock levels less than the ones associated with Maximum Sustainable Yield.
[4] Foley at el (2010) argue that the habitat can affect the intrinsic growth rate, resulting in the term $rK(S_t)$ to appear in the logistic growth function.

If $K = 0$ and $\mu > 0$, then $K(S_t) = \mu S_t$, and SAV is an essential habitat because for $S_t = 0$ 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[5]. Given the functional form given by (2′), the logistic growth function now becomes

$$F(C_t, S_t) = rC_t(K + \mu S_t)\left(1 - \frac{C_t}{K + \mu S_t}\right) \quad (2'')$$

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

$$\dot{C}_t = [r(K + \mu S_t - C_t) - qE_t]C_t \quad (3)$$

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

$$pqE_tC_t = vE_t \quad (4)$$

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

$$C = \frac{v}{pq} \quad (5)$$

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

$$E = \frac{r[(K + \mu S) - C]}{q} \; for \; \dot{C}_t = 0 \quad (6)$$

Solving (6) for C we get

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

Substituting (7) into the production function and rearranging yields

---

[5] Of course that would be against studies based on laboratory experiment (Perkings-Visser et al., 1996) and other studies (CBF Report, 2008) 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 for completion.

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

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

$$h = d_1 E + d_2 ES + d_3 E^2 \quad (9)$$

We refer to Equation (9) as the facultative habitat model. Equation (9) nests the SAV being an essential or irrelevant habitat as sub cases. For $d_1 = 0$ and $d_2 > 0$ we have that $qK = 0$ and because $q > 0$[6], this would imply that $K = 0$. Therefore, running the data for 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[7]. Barbier and Strand (1998) assume 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 will be to compute comparative static effects in equilibrium, triggered by SAV changes. The impacts of SAV changes on the blue crab fishery will be calculated assuming that the open access equilibrium described by equations (5) and (6) is stable and that fishing effort adjusts instantaneously to reach a new equilibrium. Similar to Barbier and Strand (1998) and Folley et al. (2010) 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[8]. Equation (6) of the steady-state open access equilibrium is rewritten here as

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

---

[6] It would not make any sense to set $q = 0$ because that would imply zero harvest.
[7] Again, $d_2 = q\mu$ and because $q > 0$, $d_2 = 0$ would necessarily imply that $\mu = 0$.
[8] Barbier and Strand show 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 one leads the stock to a rapid decline reducing it to near-extinction levels. As the authors argue, such a case can exist if the initial level of effort is too high given the initial stock condition (Barbier and Strand, 1985 p. 156). There is no evidence that 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.

Where the symbol * designates 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.

$$\frac{dE^*}{dS} = \frac{r\mu}{q} \qquad (11)$$

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

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

The change in revenues for the fishery is given as

$$pdh^* = \frac{r\mu v}{q}dS \qquad (13)$$

The impact of a change in SAV on effort, harvest and revenues depend 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

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

$$pdh^* = -\frac{vd_2}{d_3}dS \qquad (15)$$

Therefore in order to calculate the impacts from changes in SAV, we only require 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 $ph = vE$. Having already data on harvest and effort[9], all we need is a time-series data for price for the period 1993-2011 in order to recover v.

---

[9] Data on harvest and effort are essential for the estimation of equation (9).

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

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

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

$$h = b_0 + b_1 S \qquad (16)$$

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 before. Moreover, the comparative static effects in equilibrium, from SAV changes yield

$$dh^* = b_1 dS = \frac{vr\mu}{pq}dS$$

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

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

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

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

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

$$E = a_0 + a_1 S \qquad (17)$$

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 $\mu = 0$.

4. Data description

For the estimation of equation (9), data of aggregate SAV, effort and harvest are required. Annual Bay wide SAV coverage area in hectares was obtained from Virginia Institute of Marine Sciences (SAV program) for the years 1984-2011. For aggregate fishing effort and harvest, data were available for the three regions of the Bay where blue crab harvest takes place: Potomac River, Virginia and Maryland. Annual effort data for the Potomac River were obtained from the Potomac River Fisheries Commission for the years 1986-2011and included number of hard pots fished and the associated harvest in pounds. For Virginia portion of the Bay, annual effort data were obtained from Virginia Marine Resources Commission for the years 1993-2011. The data contain information on average annual number of pots, as well as the count of pots that contributed to that average. Therefore, we calculated the total number of hard pots for every year by multiplying these two figures. The data also include harvest of crabs in pounds caught by hard pots. The 2012 CapLog Report for Virginia indicates that almost all harvest in 2010 in Virginia (99%) was catch using hard pots.

Effort data for Maryland were available from Fisheries Administration, Maryland Department of Natural Resources. The data covered the months 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 number of gear, gear hours, hours and days fished, but we chose to use the amount of gear, in order to be compatible with the other two regions. The 2011 CapLog Report for Maryland indicates that as of 2007, 97% of the total harvest has 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 of 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 have an estimate of the aggregate amount of effort in Maryland that is comparable to the measures of effort for the Potomac and Virginia, i.e. pots. For that we calculated, for each year the catch-per-unit effort (CPUE) for both pots and trotlines in Maryland, and took the ratio of $CPUE_{pots}$ to $CPUE_{trotlines}$. By multiplying this ratio with the number of trotlines we were therefore able to convert trotline effort into pot effort for each year in the sample.

For the comparative static effects described by equations (14) and (15) additional information about price per pound and unit cost of fishing effort was required. Blue crab landings (in pounds) and dockside values data for both Maryland and Virginia were available from NOAA Fisheries: Office of Science and Technology. We were therefore able to calculate the price per pound for both states and calculate the average price in the Bay 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.

5. Empirical Results

5.1 The role of SAV as essential habitat for blue crabs

Aggregating the data for harvest and effort[10] across the three regions resulted in a sample of 19 observations for the time period 1993-2011. Table 1 below presents the summary statistics for the pooled sample

Table 1: 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(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

---

[10] As section 5 indicates, SAV data included Bay wide observations.

Our first step was to replicate the results of Barbier and Strand (1998), using their model that assumes that habitat is essential. For that 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[11]. 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 (Miller et al., 2011). Thus, there is about a 15 to 19 month lag between when crabs hatch and when they are recruited into the adult stock. Regression results are presented in table 2 below.

Table 2: 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

+p<0.10, * p<0.05, ** p<0.01, *** p<0.001;
Robust Standard errors are given in parenthesis

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

---

[11] Even though our data for harvest and effort (number of pots) were limited 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.

yields a coefficient of squared effort more statistically significant compared to its one-year-lag counterpart. Therefore, the comparative static analysis will be conducted based on the model that contains two-year lagged SAV.

As stated in section 4, the comparative static effects for the Bay are performed using expressions (14) and (15). The results for every year in our sample are presented in table 3.

Table 3: 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

On average, over the 1993-2011 period, a marginal change in SAV (1 hectare) yields a change of 6,749 pounds of blue crab harvest. In terms of revenues, the average figure from a marginal change in SAV, is 5,409 dollars. During the period 1993-2011 the Bay has experienced an average annual loss of 340.55 hectares. This is translated into approximately 2.3 million pounds loss in harvest and $1.84 million in revenues. Similar to Barbier and Strand (1998) our results so far indicate that SAV loss has negative fisheries productivity impacts on the Bay.

5.2 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 4 below.

Table 4: 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

+p<0.10, * p<0.05, ** p<0.01, *** p<0.001;
Robust Standard errors are given in parenthesis

All regressions explain equally well the variation in harvest ($R^2 = 0.93$) and the estimated coefficient of squared effort has the expected sign. However, in all specifications we reject 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 statistically insignificant. Given these results, we fail 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 the results of the Barbier and Strand model that assumes 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 (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 support 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 will also 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 (2010), because, in all specifications, both coefficients of $E * S$ and squared effort (d_2 and d_3) were found negative making counterintuitive to calculate the change in harvest and revenues from observed SAV changes[12].

To further test whether SAV matters for the crab stock, we also used our alternative approach regressing harvest on SAV, including a constant as described by equation (16) in section 3. The results are illustrated on table 5.

Table 5: 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

+p<0.10, * p<0.05, ** p<0.01, *** p<0.001;
Robust Standard errors are given in parenthesis

All specifications of SAV explain very poorly the variation in harvest (R^2). 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 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. The specification of SAV in one-year lag 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. Lastly, table 6 presents the results of the second alternative approach we used to test whether SAV matters, where effort is regressed on SAV.

---

[12] In expression (14) we have $dh^* = -\frac{vd_2}{pd_3}dS$. Having both d_2 and d_3 negative would yield dh^*/d$S < 0$ which would imply that SAV is actually detrimental to the crab stock.

Table 6: 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

+p<0.10, * p<0.05, ** p<0.01, *** p<0.001;
Robust Standard errors are given in parenthesis

The specifications of SAV in contemporaneous time and in two-year lag explained poorly the variation in harvest (R^2). Similar to our first alternative approach, the null hypothesis (that the coefficient of SAV in (16) is zero and thus µ = 0) could not be rejected indicating that that SAV does not matter as habitat for crabs. Only at 10% confidence level in the specification of SAV in one-year lag, were we able to reject the null hypothesis that the habitat does not matter for the crab stock.

Barbier and Strand (1998) assume a priori that mangrove is an essential habitat for shrimps in Campeche, Mexico. That they obtain a significantly positive coefficient of the interaction term between effort and habitat is therefore not surprising. Even though such model decisions come after studying species biology and their habitat association, or 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 to the question of how that species would behave in complete absence of its habitat. Due to this reason Foley et al. (2010) discuss the importance of empirically determining the 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 Bay's 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.

6. Discussion and policy implications

This paper investigates the habitat-fisheries interactions between two important resources in the Chesapeake Bay: Submerged Aquatic Vegetation (SAV) and blue crabs. Following the methodology by Foley et al. (2010), we construct an empirical bioeconomic model that can test whether SAV is an essential or facultative habitat for crabs. Our results show that, if we do not have perfect information on habitat-fisheries linkages, the right approach would be to run 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 run the essential-habitat model assumed in Barbier and Strand (1998). This model suggested that SAV has appositive impact for crabs. The comparative static analysis based on the essential-habitat model shows that a marginal change in SAV yields a change of 6,749 pounds in harvest and 5,409 dollars 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 loss in harvest and 1.84 million dollars in revenues. We point out that our comparative static estimates are likely to be overstated if SAV is not truly an essential habitat and we argue that this is likely the case in Barbier and Strand (1998). This is so because, when we run the more general facultative-habitat model, we find that habitat does not matter for the species, contradicting our previous results. In addition we were able to confirm this assertion using our alternative approaches (at 5% confidence level), which we showed are also valid tests of whether SAV matters. Even though there is scientific evidence (Perkings-Visser et al., 1996; CBF Report, 2007) to support the notion that SAV should be at least 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 fast 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 that 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 (2008) classifies models like the one in this paper as *equilibrium bioeconometric models* where the researcher may recover, through estimation, economic parameters, biological parameters or both. On the other hand, since data points are snapshots of nullclines, system dynamics are not well understood (Smith, 2008). Such dynamics, from both an ecological and economic point 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. There are a big number of variables, other than the simple catch-per-unit-effort adopted here, that are involved in gear equivalency (Glenn Davis, MDNR pers. comm.). Most importantly the two gears are almost never fished in the same area, with pots being used in the mainstem regions of the Bay and trotlines in rivers. This fact along with unobservable[13] 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, we acknowledge that the number of observations in our data set is rather limited. A longer time series would provide more reliable results. Smith (2008) points out that time series data for studies like ours are very limited. As more and/or better data become available in the future we plan to rerun our model and address the above limitations.

---

[13] 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 (Glenn Davis, MDNR pers. comm.).

References

Anderson, E. E. 1989. Economic benefits of habitat restoration: seagrass and the Virginia hard-shell blue crab fishery. *North American Journal of Fisheries Management*, **9**(2): 140-149.

Barbier, E. B. and I. Strand. 1998. Valuing mangrove-fishery linkages. A case study of Campeche, Mexico. *Environmental and Resource Economics*, **12**(2): 151-166.

Blue Crab. A summary brief from the Blue Crab Species Team. Ecosystem-Based Fisheries Management in Chesapeake Bay. Publication Number UM-SG-TS-2011-04.

Barbier, E. B., I. Strand and Sathirathai, S. 2002. Do open access conditions affect the valuation of an externality? Estimating the welfare effects of mangrove-fishery linkages in Thailand. *Environmental and Resource Economics*, **21**(4): 343-367.

CapLog Reports. Version 5.1, June 2012. Overview of the Virginia Commercial Blue Crab Fishery. Published by Cap Log Goup, LLC.

CapLog Reports. Version 4.05, May 2011. Overview of the Maryland Commercial Blue Crab Fishery. Published by Cap Log Goup, LLC.

Chesapeake Bay Foundation. Bad Water and Decline of Blue Crabs in the Chesapeake Bay. December 2008.

Chesapeake Bay Foundation. Climate Change and the Chesapeake Bay. July 2007.

Ellis, G. M. and A. C. Fisher. 1987. Valuing the environment as input. *Journal of Environmental Management*, **25**(2): 149-156.

Foley, N. S., V. Kahui., C. W. Armstrong., and T. M. van Rensburg. 2010. Estimating linkages between redfish and cold water coral on the Norwegian Coast. *Marine Resource Economics*, **25**(1): 105-120.

Foley, N. S., C. W. Armstrong., V. Kahui., E. Mikkelsen., and S. Reithe. 2012. A review of bioeconomic modeling of habitat-fisheries interactions. *International Journal of Ecology*. Article ID 861635.

Freeman, A. M. 1991. Valuing environmental resources under alternative management regimes. *Ecological Economics*, **3**(3): 247-256.

Heck, K. L., K. Able, C. Roman, and M. Fahay. 1995. Composition, abundance, biomass and production of macrofauna in a New England estuary: Comparisons among eelgrass meadows and other nursery habitats. *Estuaries* **18**:379–389.

Kahn, J. R. and W. M. Kemp. 1985. Economic losses associated with the degradation of an ecosystem: the case of submerged aquatic vegetation in Chesapeake Bay. *Journal of Environmental Economics and Management,* **12**(3): 246-263.

Kemp, W. M., W. R. Boynton, R. R. Twilley, J. C. Stevenson., and J. C. Means. 1983. The decline of submerged vascular plants in upper Chesapeake Bay: Summary of results concerning possible causes. *Marine Technological Society Journal* **17**: 78-89.

Krinsky, I. and A. L. Robb. 1986. On Approximating the Statistical Properties of Elasticities. *The Review of Economics and Statistics*. **68**(4): 715-719.

Lubbers, L., W. R. Boynton, and W. M. Kemp. 1990. Variations in structure of estuarine fish communities in relation to abundance of submersed vascular plants. *Marine Ecology Progress Series* **65**:1–14.

Lynne, G. D., P Conroy and F. J. Prochaska. 1981. Economic valuation of marsh areas for marine production processes. *Journal of Environmental Economics and Management*, **8**(2): 175-186.

Miller, T. Review of the Soft and Peeler Fishery for Blue Crab in the Chesapeake Bay. Report of the BBCAC Technical Work Group Charrette in Solomons, MD, August 29-30, 2001. Report No 3.

Miller, T. J., Wilberg., M. J., A. R. Colton et al., Stock Assessment of Blue Crab in Chesapeake Bay 2011. Final Assessment Report. Ref[UMCES] CBL 11-011.

Perking-Visser, E., T. G. Wolcott and D. L. Wolcott. 1996. Nursery role of seagrass beds: enhanced growth of juvenile blue crabs (Callinectes sapidus Rathbun). *Journal of Experimental Marine Biology and Ecology*. **198**: 155-173.

Sathirathai, S. and E. B. Barbier. 2001. Valuing mangrove conservation in Southern Thailand. *Contemporary Economic Policy*, **19**(2): 109-122.

Smith, M. D. 2008. Bioeconometrics: Empirical Modeling of Bioeconomic Systems. *Marine Resource Economics*, **23**: 1-23.

Swallow, S. K. 1994. Renewable and nonrenewable resource theory applied to coastal agriculture, forest, wetland and fishery linkages. *Marine Resource Economics*, **9**(4): 291-319.

References from the Web

Virginia Institute of Marine Sciences. SAV Program monitors and restores bay grasses. A healthy Bay is a grassy Bay:
http://www.vims.edu/features/programs/sav.php Visited at: 07/01/2012.

NOAA Chesapeake Bay Office. Blue Crab:
http://chesapeakebay.noaa.gov/fish-facts/blue-crab Visited at: 07/01/2012

U.S. Fish and Wildlife Service, Chesapeake Bay Field Office. Where Have All the Grasses Gone?:
http://www.fws.gov/chesapeakebay/cbsav.html   Visited at: 05/23/2013

Data links and contact information

Fisheries Administration, Maryland Department of Natural Resources, Connie Lewis, email:
clewis@dnr.state.md.us Contacted for effort and harvest data in Maryland: 07/16/2012

Virginia Institute of Marine Sciences. SAV in Chesapeake Bay and Coastal Bay. Submerged Aquatic Vegetation (SAV) in Chesapeake Bay and Delmarva Peninsula Coastal Bays:
http://web.vims.edu/bio/sav/index.html Visited at 07/05/2012

NOAA Fisheries: Office of Science and Technology:
http://www.st.nmfs.noaa.gov/st1/commercial/index.html
Visited 07/05/2012

Potomac River Fisheries Commission, Ellen Cosby: Ellen.prfc@verizon.net. Contacted for effort and harvest data in Potomac River on 07/19/2012

Virginia Marine Resources Commission, Samantha M. Hoover, Fisheries Management Specialist,   Plans/Statistics   Department.   Phone: 757-247-2115.   Email:

Samantha.Hoover@mrc.virginia.gov. Contacted for effort and harvest data in Virginia and 03/12/2013.

NOAA Fisheries: Office of Science and Technology:

http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index

Visited at: 05/03/2013.

Personal Communication

Glenn Davis. Blue Crab Program: Maryland Department of Natural Resources.

Email: gdavis@dnr.state.md.us   Contacted at: 03/27/2013