Efficient harvest regimes for a sedentary fishery: The case of the Eastern Oyster in the Chesapeake Bay

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Abstract

We investigate the role of harvest sanctuaries and reserves in the management of a sedentary fishery. An optimal control bioeconomic model is developed and optimized for native oysters in the Chesapeake Bay that incorporates two positive externalities generated by oyster stocks: nutrient removal and provision of habitat for other benthic species. The model incorporates four management regimes that currently exist in the Bay: public grounds, aquaculture on leased grounds, sanctuaries that are never harvested, and reserves that are infrequently harvested for short periods. We find that if harvest effort in public grounds can be controlled, then that management regime unambiguously provides the highest social welfare. However, if harvest effort in public grounds cannot be controlled, then reserves provide the highest social welfare. Sanctuaries are part of the optimal mix of regimes only when harvest effort on public grounds cannot be controlled and a pulsed harvest is not feasible.

1. Introduction

Management of complex economic-ecological systems often involves simultaneous existence of different spatially-explicit regimes to achieve desired goals. In the context of marine resources, there is increasing interest in the use of two types of protected areas – sanctuaries, which are never harvested, and reserves, which are pulse-harvested at intervals - as means to increase fish production, harvest and resource rents.

Prior research on marine management systems has focused on economic decisions, interactions and spillovers from either a sanctuary or a reserve, both treated as no-harvest zones, to the neighboring public grounds (Holland and Brazee, 1996; Hannesson, 1998; Holland, 2000; Anderson, 2002; Pezzey et al., 2000; Sanchirico and Wilen, 2001, 2002) or from aquaculture to the public area (Mikkelsen, 2007). Most of this research has been conducted in the context of marine species that are mobile as adults (e.g. Hannesson, 1998; Holland, 2000). With a mobile fish species, fishermen can harvest fish that were born and grew in a protected area and subsequently migrated (Anderson, 2002; Hannesson, 1998). This migration can be due to density differences between patches (Holland and Brazee, 1996) or other sink-source mechanisms (Sanchirico and Wilen, 2001). In a few studies (e.g. Pezzey et al., 2000), mobile species are modeled as being attached to their habitat (reef). In such models the efficiency of protected areas depends on initial biologic conditions instead of economic variables and/or parameters (Pezzey et al., 2000).

A general result from this literature is that, if harvest effort cannot be controlled in the areas that are open for fishing (the public grounds), then all benefits from protected areas are dissipated (Holland and Brazee, 1996; Holland, 2000; Anderson, 2002). Another important result is that no-harvest zones have the potential to increase both fish biomass and harvest in the case where effort in public grounds cannot be perfectly controlled (Sanchirico and Wilen, 2001). These results depend on the fish having some degree of mobility as adults. Pulsed harvest from reserves, as opposed to no-harvest areas (sanctuaries), has the advantage of instantaneously boosting fishermen's income while promoting some degree of stock protection. However, this relative attractiveness is also contingent on species' mobility. To our knowledge, there is no prior research incorporating the two management systems simultaneously. In this paper we examine

the potential role of sanctuaries and reserves in the management of a species that is sedentary as adult, the Eastern oyster (*Crassostrea Virginica*) in the Chesapeake Bay (the Bay hereafter).

The Eastern oyster is an interesting case study because it is a keystone species in the Bay from both a commercial (Lipton, 2008; CBF Report, 2010 p.6) and an ecological point of view. In addition to commercial harvest, oysters provide two important ecological functions. First, they filter water and remove nutrients from the systems. They do this in two ways: a) by accelerating denitrification in sediments of nutrients that have passed through the oyster (Newell, 2004) and b) through nutrient assimilation in the species' shell and meat and subsequent removal through harvest (Chesapeake Bay TMDL, Appendix U). Second, oyster reefs provide habitat and shelter, as well as valuable sources of food for many other species (CBF Report, 2010).

Currently, oysters in the Bay are managed under four spatially-segregated regimes: sanctuaries, which are permanently closed to harvest; reserves, which are closed to harvest most of the time, but periodically opened for pulsed harvest; aquaculture conducted on private leased grounds; and public grounds that are open to harvest each year. We develop a bioeconomic model of oysters in the Bay that includes these four management regimes. The model incorporates the fact that oysters are mobile when very young, but sedentary thereafter. We optimize the model to determine whether there exists a set of circumstances where it is socially optimal to simultaneously have all four management regimes. The model we analyze can be used to address any setting where permanent harvest restrictions, pulsed and continuous harvest take place simultaneously. It also applies to relatively immobile marine species such clams, mussels and urchins.

The model also incorporates the effects of oysters on nutrients in the Bay and on other species. Nutrient assimilation and removal through harvest is modeled explicitly, rather than being included as part of the natural decay of nutrients in the Bay (as in Carpenter et al., 1999; Brock and Starrett, 2003). Interactions between exploited species and other species have been explored before, but typically in the context of predator-prey dynamics (e.g. Kar and Chakraborty, 2009). These spillovers from oysters on nutrient dynamics and the dynamics of other species introduce complexities when considering the optimal timing of pulsed harvest from reserves. Impulsive optimal control theory has been used to considering optimal timing and degree of harvest in applications including aquaculture (Karp et al., 1986; Yu and Leung, 2006)

and forestry (Bergland et al., 2006; Termansen, 2007). In the presence of spillover effects between a species that is pulse harvested and other state variables, the harvest pulse has implications for the control variables for the other state variables in the system.

In this paper we develop, characterize and explore numerically a deterministic optimal control model that tracks oyster stock in each management area, along with the stock of a second species (in our model, the blue crab), which captures biodiversity spillovers, and a nutrient pollutant (in our model, nitrogen) in the system. We examine the sensitivity of results under two cases: optimal regulated fishing effort and open-access. Under either case, the results indicate that it is not socially optimal for the four management systems to coexist simultaneously. When effort is optimally regulated, public harvest in the entire area is the first-best outcome. If some portion of the system is to be closed to harvest, reserves generate higher social welfare than sanctuaries. If effort in the public grounds cannot be controlled, i.e. the public grounds are open access; the first-best strategy is to manage the entire Bay as reserves. When this outcome cannot be attained a combination of reserve and sanctuaries constitutes the second-best strategy.

In Section 2 the bioeconomic model is described. Analytical optimality results for both continuous control variables and discrete jumps in state variables are derived and interpreted in Section 3. Specific functional forms and parameter values are described in Section 4. Simulation results are presented in Section 5. The results and their policy implications are discussed in Section 6.

2. A Model of four harvest regimes, two species and externalities

2.1 Description of biology and economic decisions in oyster regimes

We begin with some preliminary notation and basic assumptions. Let a_j be the amount of area devoted to each management system, with $j = S, A, R, P$ for sanctuary, aquaculture, reserve and public grounds. The four management systems do not spatially overlap with each other. In each area, the stock of oysters, O_j, measures the biomass of market-sized oysters, measured per unit area[1]. The Bay's average stock per unit area (O) is then the weighted average of the populations in the four areas:

$$O = \frac{\sum_j a_j O_j}{\sum_j a_j} = \frac{\sum_j a_j O_j}{a_{BAY}}, j = S, R, A, P$$

where $a_{BAY} = \sum_j a_j$ is the total area suitable for oysters in the Bay.

All areas in the Bay are assumed to be homogenous in the sense that there is no difference in stock productivity coming from different bottom conditions[2]. Oyster stocks in each area grow from somatic growth of already-settled oysters and from recruitment of new oysters. Oyster larvae (juveniles) are free-swimmers and can be transported from one area to another depending on water currents (CBP, 2004). We assume that larvae are mixed and randomly distributed throughout the Bay. Recruitment in each area therefore depends on the adult stock of oysters in all areas. We refer to this ecological property of oysters as the *stock spillover*. Stock dynamics in all areas, except aquaculture which will be modeled separately, therefore consist of two elements:

$$\dot{O}_j = F(O_j) + I(O), \quad j = S, P, R. \quad (1)$$

where, $F(O_j)$, captures somatic growth and $I(O)$ captures recruitment. We conjecture that $\frac{\partial F}{\partial O_n} \geq 0$ for low levels of O_n and $\frac{\partial F}{\partial O_n} < 0$ for high levels, and that $\frac{\partial I}{\partial O} \geq 0$.

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[1] The terms "adult", "harvestable" and "market-sized" oyster will be used interchangeably here.
[2] Differentiating the productivity of each area would imply modeling the supply of oyster seed and shell, both of which determine the quality of bottom condition.

For sanctuaries, where no harvest is allowed, stock dynamics are given by (1) since harvest is not permitted in the area. In the public area, the stock is reduced by harvest, H_P. Adopting the Schaefer production function (Clark, 1990) with q_O and E_P being the catchability coefficient and oyster harvest effort per unit area respectively, expression (1) is rewritten as

$$\dot{O}_P = F(O_P) + I(O) - q_O E_P O_P$$

Watermen in public grounds are price takers (P_O denotes oyster unit price) and with v being the unit cost of effort, rents per unit area are

$$\Pi_P = P_O q_o E_P O_P - v E_P.$$

E_P is either a control variable chosen by the management agency (in the case where effort is managed) or determined by the harvesters (in the open access case). In the open access case, effort will enter the fishery until rents are dissipated, which occurs when

$$O_P = \frac{v}{P_O q_o}.$$

The model assumes that there is one reserve. Multiple reserves could be modeled, but would require determination of optimal harvest timing for each modeled reserve. The reserve is opened for harvest at time T_R^i, with $i = 1, \dots, k$ being the number of openings and $k \to \infty$. Each time the reserve opens for harvest, effort enters at a rate E_R for a short time period, τ^3. The pulse of harvest from the reserve will end when the reserve reaches the open access equilibrium stock level, at which point fishing effort will cease

$$O_R(T_R^i + \tau) = \frac{v}{P_O q_O}$$

T_R^i is a choice variable. The optimal timing of the harvest pulse in the reserve will be addressed in the next section.

The fourth regime is the area leased to aquaculture. Commercial oyster aquaculture in the Bay consists of two types: contained off-bottom, which uses cages or floating rafts, and on-bottom, a method that involves spreading seed oysters on shell at the bottom and allows them to

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[3] The variable τ is typically measured in days. It is used here only for notational purposes without further application.

grow (Wieland, 2008a). Even though its off-bottom counterpart is emerging, on aggregate, on-bottom lease is the most common type of aquaculture in the Bay[4]. Virginia has a long and commercially successful history of oyster aquaculture, coupled with an efficient institutional framework to manage the industry (Wieland, 2008a). Maryland is updating its laws and increasing the percentage of oyster bars available for leasing. Because aquaculture areas are intensively managed, the biology of the oysters in these systems is likely very different from the biology of oysters in the other three areas in the Bay. We do not account for aquaculture stock dynamics. Rather, we assume that the stock per unit area, O_A, is determined by the aquaculture operator, and is constant. The economic decisions in aquaculture are modeled as a simple production volume model with quadratic costs. With P_O, y and H_A being the exogenous price, cost parameter and volume of oyster production measured in per unit area terms, rents in aquaculture are given as

$$\Pi_A = P_O a_A H_A - y a_A H_A^2$$

While we do not attempt to model the biology of oysters in aquaculture, it is necessary to model the impact that aquaculture oysters have on bay-wide recruitment. For this purpose, the density of oysters in the aquaculture area is assumed to be $O_A = K_O / 2$, where K_O is the carrying capacity for oysters.

2.2 Biology and economic decisions for blue crabs

Blue crabs are assumed to be uniformly distributed in the entire area with their population being positively affected by oyster abundance (CBF Report, 2010 p.14). The impact of oyster stock on crab productivity could be modeled through an effect on either blue crabs' intrinsic growth rate, carrying capacity or both. Such an effect can be generically presented in the crab state equation as

$$\dot{C} = F_C(C, O) - q_C E_C C$$

where F_C represents the growth of blue crabs (including recruitment) as a function of the species' stock and of the Bay's aggregate oyster stock. The dependence of F_C on O represents the second

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[4] The "most common type" of oyster aquaculture is defined in terms of area devoted to on-bottom type and profitability (Webster. D. W. and Wieland R. pers. communication).

ecological property of oysters modeled here, which we call the *biodiversity spillover*. It is conjectured that $\frac{\partial F_C}{\partial C} \geq 0$ for low levels of C and $\frac{\partial F_C}{\partial C} < 0$ for high levels of C, as well as $\frac{\partial F_C}{\partial O} > 0$ and $\frac{\partial^2 F_C}{\partial O^2} \leq 0$. Watermen are price takers (P_C) and, with m being the unit cost of effort, rents are given by

$$\Pi_C = P_C q_C E_C C - m E_C$$

Similar to oystering in the public area, E_C could either be a control variable or could be determined by an open access equilibrium.

2.3 Description of nitrogen dynamics

The pollutant we examine is nitrogen, but our analysis is applicable to other pollutants like phosphorus. Let $\bar{L}$ be the loadings of the pollutant into the Bay. For simplicity, we ignore nitrogen recycling (internal loading) and focus only on elements of nitrogen dynamics that can be affected by management. The management agency can reduce loadings by an amount R by encouraging adoption of upstream best management practices (BMP), at the constant unit cost l. R is a control variable. Let d be the percent rate of natural decay of nitrogen in the Bay excluding nitrogen removal associated with oysters. Oysters cause removals of nitrogen through two mechanisms. First, when oysters are harvested, some nitrogen located in the oysters' shell and meat is removed as well. Total harvest from reserves, public grounds and aquaculture is given by H_O, a proportion, s, of which is nitrogen. Second oysters speed the rate of denitrification in sediments. Denitrification by oysters is assumed to be a linear function of the Bay's stock, with ρ being the constant denitrification rate per adult oyster present in all areas. The state equation for nitrogen is then given by:

$$\dot{N} = \bar{L} - R - \rho a_{BAY} O - s H_O - dN$$

The effect of parameters ρ and s on nitrogen dynamics constitutes the third ecological property of oysters, which we will refer to as *environmental spillovers* related to Bay's aggregate stock and harvest respectively. The term "spillover" here indicates explicit modeling, compared to the approach where they are included in the natural decay of the pollutant. The initial condition for nitrogen in Bay's water body is $N(0) = N_0$.

2.4 The objective function

The social welfare function (SW) contains two parts: a continuous part (CB), associated with revenues and costs occurring at all points in time, and a discrete part (IB) that captures the instantaneous costs and benefits that occur when the reserve is opened for harvest. In the next subsection we describe the continuous part of the objective function whereas the following subsection deals with the discrete one.

2.4.1 The continuous part of objective function

Harvests of oysters from the public grounds and from aquaculture and crabs occur continuously. The value of harvest from public grounds is given by $P_O a_P q_o E_P O_P$ and cost of effort is given by $a_P v E_P$. Harvest and cost from aquaculture also occur continuously. Maximizing rents in aquaculture (Π_A) yields a maximized level of total harvest equal to $H_A^* = a_A \frac{P_O}{2y}$ and a total cost of $a_A \frac{P_O{}^2}{4y}$. The value of harvest of crabs is given by $P_C q_C E_C C$ while the cost of crab effort is mE_C.

Turning to nitrogen, the social benefit from the Bay that is affected by its nitrogen concentration is given by U(N). This is measured in monetary terms, and includes all use and nonuse values generated by the Bay other than oyster harvest and crab harvest. It would include residential values, recreational values, aesthetic values, and existence values. It is conjectured that $U'(N) < 0$ and $U''(N) \geq 0$. Efforts to reduce nitrogen, through BMPs, come at a cost, Rl.

Summing over all continuous benefits and costs gives the continuous part of the social welfare function,

$$CB = \int_0^\infty \left\{ P_O \left[a_P q_O E_P O_P + a_A \frac{P_O}{2y} \right] + P_C q_C E_C C + U(N) - Rl - a_P v E_P - a_A \frac{P_O{}^2}{4y} - mE_C \right\} e^{-\delta t} dt.$$

Two management costs are not included in this analysis. First, when sanctuaries are created, the management agency typically incurs costs associated with reef creation and/or restoration activities. These are not incorporated in the model because it is difficult to reliably model the impact these activities have on subsequent oyster productivity. Second, no

enforcement or monitoring costs are included, because these do not tend to vary across different management regimes[5].

2.4.2 The discrete part of objective function

The opening of reserve at T_R^i will cause the stock in the reserve to exhibit a negative jump from the harvest pulse. The magnitude of the jump is given as

$$O_R(T_R^{i+}) - O_R(T_R^{i-}) = \left[\frac{v}{P_O q_O} - O_R(T_R^{i-})\right] d_R(T_R^i), \text{ with } d_R(T_R^i) = 1 \text{ at } i = 1, ..., k \text{ with } k \to \infty.$$

In the literature of impulsive optimal control theory (Seierstad and Sydsæter, 1987) $O_R(T_R^{i+})$ and $O_R(T_R^{i-})$ denote the right and left hand limits respectively of $O_R(T_R^i)$.

Having defined the magnitude of the jump and the rule for when effort will cease (see section 2.1), we need to determine the cost of effort during the pulse. While stock dynamics before the reserve opening are given by (1), the harvest pulse is short enough that we can ignore stock growth during the pulse, so that the stock changes only due to harvest

$$\dot{O}_R = -q_O E_R O_R$$

Integrating over the harvest interval $\left[T_R^i, T_R^i + \tau\right]$, simplifying, solving for effort per unit area[6] and multiplying with its unit cost we get

$$vE_R = \frac{v}{q_O} \ln\left[\frac{O_R(T_R^{i-})}{O_R(T_R^{i+})}\right] = \frac{v}{q_O} \ln\left[\frac{O_R(T_R^{i-})}{v/P_O q_O}\right] \quad (2)$$

where E_R is the effort per unit area applied during the pulse. The value of oyster harvest and the cost of effort during the pulse are elements of what we will call instantaneous benefit function, IB.

Because of the biodiversity spillover, the jump in the stock in the reserve will instantaneously affect the optimal density of blue crabs. Therefore, when the reserve is opened for harvest, the regulatory agency would want to apply a pulse of effort for crabs, so that its stock

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[5] Lt. Kirkwood, Maryland Natural Resource Police, pers. communication.
[6] $O_R(T_R^i)$ is essentially the same as $O_R(T_R^-)$.

would also experience a jump. Letting b_{ci} be the percentage of the crab stock harvested in the ith opening, the magnitude of the jump in crabs is

$C(T_R^{i+}) - C(T_R^{i-}) = -b_{ci}C(T_R^{i-})$, at $i = 1, \dots, k$ with $k \to \infty$ and $b_{ci} = [0,1]$.

In the literature of optimal control with jumps in state variables, b_{ci} is referred to as jump parameter and has its own necessary condition (Seierstad and Sydsæter, 1987) as we will see later. To derive the cost of crab effort during the pulse we utilize (2), making the necessary notational changes in stock, unit cost effort, catchability coefficient, as well as the equation for the magnitude of the jump. With these changes the instantaneous cost of crab effort during the pulse is

$$\frac{m}{q_C} ln\left[\frac{C(T_R^{i-})}{C(T_R^{i+})}\right] = \frac{m}{q_C} ln\left[\frac{1}{(1 - b_{ci})}\right]$$

Similarly, because of the stock spillover, the opening of the reserve should trigger a jump in the stock of oysters in the public grounds. As in the case of crabs, if we define the jump parameter b_{Pi} as the percentage of the public oyster stock harvested in the ith opening, the magnitude of the jump will be

$O_P(T_R^{i+}) - O_P(T_R^{i-}) = -b_{Pi}O_P(T_R^{i-})$, at $i = 1, \dots, k$ with $k \to \infty$ and $b_{Pi} = [0,1]$.

Following the same approach, the cost per unit area of effort associated with the jump in the public grounds stock during the pulse can be shown to be

$$\frac{v}{q_o} ln\left[\frac{O_P(T_R^{i-})}{O_P(T_R^{i+})}\right] = \frac{v}{q_o} ln\left[\frac{1}{(1 - b_{Pi})}\right]$$

Finally, it will be shown that when the reserve is opened for harvest, it will be optimal to adjust the amount of nitrogen in the Bay, through an instantaneous decrease in BMPs. This is because the pulse of harvest in the reserve and public area removes a discrete quantity of nitrogen, allowing the management agency to credit that amount of nitrogen reduction. The magnitude of the jump in nitrogen due to the removal through harvest during the pulse is given by

$$N(T_R^{i+}) - N(T_R^{i-}) = s\left[a_R\left(O_R(T_R^{i-}) - \frac{v}{P_O q_O}\right) + a_P b_{Pi} O_P(T_R^{i-})\right] d_N(T_R^i), \quad \text{with} \quad d_N(T_R^i) = 1 \quad \text{at}$$

$i = 1, \dots, k$ with $k \to \infty$.

This nitrogen removal is valued at the cost of nitrogen removal, l.

The Net Present Value of total instantaneous benefits (IB), related to each jump is then given by

$$IB = \sum_{i=1}^{k}\left\{P_O\left[a_R\left(O_R(T_R^{i-}) - \frac{v}{P_O q_O}\right) + a_P b_{Pi} O_P(T_R^{i-})\right] - a_R \frac{v}{q_O}\ln\left(\frac{O_R(T_R^{i-})}{v/P_O q_O}\right)\right.$$

$$- a_P \frac{v}{q_O}\ln\left[\frac{1}{(1-b_{Pi})}\right] + P_C b_{ci} C(T_R^{i-}) - \frac{m}{q_C}\ln\left[\frac{1}{(1-b_{ci})}\right]$$

$$\left. + s\left[a_R\left(O_R(T_R^{i-}) - \frac{v}{P_O q_O}\right) + a_P b_{Pi} O_P(T_R^{i-})\right]l\right\}e^{-\delta T_R^i}$$

where δ is the discount rate and the last term represents BMP cost savings. As in CB, the first term in brackets, multiplied by P_O defines total revenues from oyster harvest, here from jumps in reserve and public grounds. The next four terms capture total costs of effort in reserve and public grounds, as well as net revenues associated with the jump in blue crab stock. We can now fully present the complete problem to be characterized and simulated. This is given below

$$\max_{R, E_C, E_P, T_R^i} SW = CB + IB$$

S.t.

$$\dot{O}_S = F(O_S) + I(O) \text{ for all } t$$

$$\dot{O}_P = F(O_P) + I(O) - q_O E_P O_P \text{ for all } t \neq i$$

$$O_A = K_O/2 \text{ for all } t$$

$$\dot{O}_R = F(O_R) + I(O) \text{ for all } t \neq i$$

$$\dot{C} = F_C(C, O) - q_C E_C C \ t \neq i$$

$$\dot{N} = \bar{L} - R - \rho a_{BAY} O - s\left(a_P q_O E_P O_P + a_A \frac{P_O}{2y}\right) - dN \text{ for all } t \neq i$$

$$\text{with } O = \frac{\Sigma_j a_j O_j}{a_{BAY}}, j = S, R, A, P \text{ and } N(0) = N_0$$

In the next section of the paper, we derive the optimality and arbitrage conditions for both the continuous and discrete case parametrically i.e. taken the amount of area in each management system as given. In the simulation part later on, different scenarios of area allocation are examined and the efficiency of management systems, under both cases, is compared.

3. Analytical Results

3.1 The continuous case

The current-value Hamiltonian is

$$H = P_O \left[a_P q_O E_P O_P + a_A \frac{P_O}{2y} \right] + P_C q_C E_C C + U(N) - Rl - a_P v E_P - a_A \frac{P_O{}^2}{4y} - m E_C$$

$$+ \lambda_S [F(O_S) + I(O)] + \lambda_R [F(O_R) + I(O)] + \lambda_P [F(O_P) + I(O) - q_O E_P O_P]$$
$$+ \lambda_C [F_C(C, O) - q_C E_C C]$$
$$+ \lambda_N \left[\bar{L} - R - \rho a_{BAY} O - s \left(a_P q_O E_P O_P + a_A \frac{P_O}{2y} \right) - dN \right]$$

The first order condition for the amount of nitrogen reduced through BMPs is

$$\frac{\partial H}{\partial R} = -l - \lambda_N = 0 \rightarrow \lambda_N = -l \quad (3).$$

λ_N is a negative number that represents all future disutility, in current monetary terms, from a marginal increase in the nitrogen stock, and will be referred to here as the future value of nitrogen. Because R shows up linearly in the Hamiltonian, equation (3) states that R should be rapidly increased or decreased (bang-bang control) so that at all points in time the future value of nitrogen to be equal to the constant cost of removing it. It holds also that $\dot{\lambda}_N = 0$.

The first order condition for crab effort is:

$$\frac{\partial H}{\partial E_C} = \{ P_C q_C C - m - \lambda_C q_C C \leq 0, E_C \geq 0, [P_C q_C C - m - \lambda_C q_C C] E_C = 0 \}$$

$$\rightarrow P_C - \frac{m}{q_C C} \leq \lambda_C$$

The LHS of the above inequality is the net benefit from a unit of crab, whereas the RHS is the current value of having one more crab in the stock. λ_C is known as the shadow value or the user cost of stock. Whenever λ_C exceeds $P_C - \frac{m}{q_C C}$, the crab stock should be allowed to expand by ceasing all crab harvest. Whenever $P_C - \frac{m}{q_C C} > \lambda_C$ crab effort should be employed at the maximum rate that harvest capacity allows. The process will continue until $P_C - \frac{m}{q_C C} = \lambda_C$ (4), which holds at the singular solution for the crab stock and constitutes a standard result in the literature of renewable resources.

The adjoint equation for the crab stock, after rearranging, becomes

$$\dot{\lambda}_C = \lambda_C(\delta - F_C') - P_C q_C E_C + \lambda_C q_C E_C$$

where $F_C' = \frac{\partial F_C(C,O)}{\partial C}$. At the singular solution, the adjoint equation for the crab stock and its state equation, following standard steps (Conrad and Clark, 1987 p.75), gives

$$\delta = F_C' + \frac{m F_C(C,O)}{C[P_C q_C C - m]} \quad (5)$$

Given O, expression (5) is the arbitrage condition that implicitly solves for C^*, the singular solution for the crab control problem. This expression is known as "fundamental equation of renewable resources" (Conrad, 1999 p.14) and implies that at all times the marginal net growth rate plus the marginal stock effect (the two known as resource's internal rate of return) should equal the discount factor. As for the marginal stock effect, it is the ratio of the marginal value of the stock $m F_C(C,O)/C$ relative to the marginal value of effort $P_C q_C C - m$. Equation (5) is another standard result and will serve as the baseline for comparison with a similar, but extended expression, for the public oyster stock.

The first order condition for effort in public oyster grounds, after rearrangement, yields

$$P_O - \frac{v}{q_O O_P} - s\lambda_N = \frac{\lambda_P}{a_P} \quad (6)$$

Optimality condition (6) states that the user cost of a decrease in oyster density in the public grounds (the RHS) should equal the net benefit from catching the oysters plus the marginal value of removing nitrogen through oyster harvest (the LHS).

The adjoint equation for the public oyster stock upon simplification becomes

$$\dot{\lambda}_P = \lambda_P\big(\delta - F'(O_P)\big) - \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R + \lambda_P) - P_O a_P q_O E_P + \lambda_P q_O E_P - \lambda_C \frac{\partial F_C}{\partial O_P}$$
$$+ \lambda_N(a_P \rho + s a_P q_O E_P) \quad (7)$$

Expression (7) will be used to derive the arbitrage condition for the public oyster stock later and will not be interpreted here. The adjoint equation for the stock in the reserve yields

$$\dot{\lambda}_R = \lambda_R\big(\delta - F'(O_R)\big) - \frac{\partial I}{\partial O_R}(\lambda_S + \lambda_R + \lambda_P) - \lambda_C \frac{\partial F_C}{\partial O_R} + a_R \rho \lambda_N \quad (8)$$

Similarly, the adjoint equation for the stock in the sanctuary becomes

$$\dot{\lambda}_S = \lambda_S\big(\delta - F'(O_S)\big) - \frac{\partial I}{\partial O_S}(\lambda_S + \lambda_R + \lambda_P) - \lambda_C \frac{\partial F_C}{\partial O_S} + a_S \rho \lambda_N \quad (9)$$

Equations (8) and (9) state that the rate of change in the value of oysters in the reserve and/or sanctuary (in situ value) should equal the extent to which the opportunity cost of future stock value exceeds the marginal impact of current stock on its future in situ value, adjusted by three terms: a) the marginal impact of current stock on the future user cost of stocks in all areas affected by stock spillover, b) the marginal impact of current crab stock on its user cost attributed to the biodiversity spillover and c) the marginal impact of current total denitrification rate on the future value of nitrogen. The adjoint equation for nitrogen, with $\dot{\lambda}_N = 0$, yields

$$\lambda_N = \frac{U'(N)}{(\delta + d)} = -l \quad (10)$$

Similar to λ_N, $U'(N)$ is negative and represents people's willingness to pay (WTP) for reduced nitrogen. Expression (10) states that the user cost of nitrogen equals people's WTP for ambient nitrogen reductions accounting for the discount rate and the natural decay of the pollutant. Optimal management requires the unit cost of nitrogen reduction from best management

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practices to be set at that level. One important result of (10) is that, if $U(N)$ is not changing over time, then $U'(N)$ will be constant, which implies that the optimal N will also be constant over time.

Turning now to equation (7), we will try to give it a form similar to (5). Using (6), (7), the state equation for public oyster stock and following the steps in Conrad and Clark (1987 p.75) we obtain (details are provided in the Appendix)

$$
\delta = \left[F'(O_P) + \frac{\partial I}{\partial O_P} \right] + \frac{v[F(O_P) + I(O)]}{O_P(P_O q_O O_P - v - s\lambda_N q_O O_P)}
$$
$$
+ \frac{q_O O_W}{a_P(P_O q_O O_P - v - s\lambda_N q_O O_P)} \left\{ \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R) + \lambda_C \frac{\partial F_C}{\partial O_P} - a_P \rho \lambda_N \right\} \quad (11)
$$

Arbitrage condition (11) is an extended version of (5). The first RHS term represents the marginal net growth rate. While $F'(O_P)$ captures the effect the area's stock has on its own somatic growth excluding recruitment, the term $\frac{\partial I}{\partial O_P}$ represents the effect of the area's stock on its recruitment through the stock spillover. Given the way $F(O_P)$ is modeled, the first RHS term in (11) is the same as F'_C from (5). The second RHS term of (11), as in (5), represents the marginal stock effect i.e. the marginal value of the stock $\left(\frac{v[F(O_P)+I(O)]}{O_P}\right)$ relative to the marginal value of effort $(P_O q_O O_P - v - s\lambda_N q_O O_P)$. One difference is that the marginal value of the stock now incorporates recruitment coming from the whole Bay (stock spillover). Moreover, the marginal value of effort captures the rate at which the value of nitrogen is affected by nitrogen removal through harvest $(s\lambda_N)$.

The third RHS term constitutes additional marginal stock effects. Note that the marginal value of effort is the same. The term $\left\{ \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R) + \lambda_C \frac{\partial F_C}{\partial O_P} - a_P \rho \lambda_N \right\}$ in (11) captures the marginal impact of current stock on the in situ value of the stock in neighboring areas due to stock spillovers, on the future value of crabs due to the biodiversity spillover (change in oyster abundance), and on the value of nitrogen through denitrification. All additional marginal stock effects are positive, providing the incentive to have more stock in the water leaving it longer unharvested compared to a situation where these spillovers are ignored.

3.2 Optimization at the jump points

In what follows we adopt the approach by Seierstad and Sydsæter (1987) regarding the necessary conditions when there are jumps in state variables. At the jumps points, the necessary condition for the stock in reserve becomes

$$\lambda_R(T_R^{i-}) = a_R \left[P_O - \frac{v}{q_O O_R(T_R^{i-})} + sl \right] \quad (12)$$

Equation (12) states that the shadow value of the stock right before the jump should equal net harvest revenues and cost savings in BMPs (sl), at that point in time. The necessary condition for crabs at the jump points is

$$[1 - b_{ci}]\lambda_C(T_R^{i+}) + P_C b_{ci} = \lambda_C(T_R^{i-}) \quad (13)$$

Equation (13) has the economic interpretation that at all jump points, the value of the unharvested portion of the stock $(1 - b_{ci})$ right after the jump along with the revenue from the harvested portion (b_{ci}), should equal the value of the stock right before the jump. Similarly, the necessary condition for public oysters at the jump yields

$$[1 - b_{Pi}]\lambda_P(T_R^{i+}) + P_O a_P b_{Pi} = \lambda_P(T_R^{i-}) \quad (14)$$

The necessary condition for nitrogen at the jump is

$$\lambda_N(T_R^{i+}) - \lambda_N(T_R^{i-}) = 0 \text{ or } \lambda_N(T_R^{i+}) = \lambda_N(T_R^{i-}).$$

Therefore, the costate variable for nitrogen is continuous. This is so because both the instantaneous benefit function and the expression for the magnitude of the jump in nitrogen are independent of N.

We now turn into the necessary conditions about the jump parameters. Following condition 75 from Seierstad and Sydsæter (1987 p.197) for b_{ci} we have.

$$\frac{\partial IB}{\partial b_{ci}} + \lambda_C(T_R^{i+}) \frac{\partial \left[-b_{ci} C(T_R^{i-}) \right]}{\partial b_{ci}} = 0$$

which, after solving for b_{ci}, plugging back into (13) and simplifying yields

$$P_C - \frac{m}{C(T_R^{i-})q_C} = \lambda_C(T_R^{i-}) \quad (15)$$

Expression (15) simply confirms what one might expect. The net benefit from catching and selling a crab should equal its user cost at all times. A comparison with equation (4) confirms that. The steps for the public stock are identical, obtaining

$$\left[P_O - \frac{v}{q_o O_P(T_R^{i-})} - s\lambda_N \right] = \frac{\lambda_P(T_R^{i-})}{a_P} \quad (16)$$

Finally we have the expression for the optimal timing of the jump in the reserve. That is given by

$$H(T_R^{i+}) - H(T_R^{i-}) - \delta IB = 0 \quad (17)$$

This is an arbitrage condition that states that the reserve should be opened for pulsed harvest when the difference between all instantaneous and future benefits from delaying its opening $H(T_R^{i+})$ versus opening it earlier $H(T_R^{i-})$, should equal the opportunity cost of delaying the jump (δIB).

4. Numerical analysis and specification of cases and scenarios

In order to simulate the system, it is necessary to choose specific functional forms for oyster and blue crab dynamics. For oyster growth equation in all areas except aquaculture, we assume that the stock grows logistically having a linear additive term representing the stock spillover:

$$F(O_n) + I(O) = r_o O_n \left(1 - \frac{O_n}{K_O} \right) + \varphi O, \quad n = S, P, R$$

The parameters r_o and K_O are oysters' intrinsic growth rate and carrying capacity respectively, while φ represents the effect Bay's stock per acre has on recruitment in each area through larval dispersal. Blue crabs are also assumed to grow logistically, but at a rate partially determined by the oyster stock. Specifically, the oyster stock is assumed to influence the Bay's carrying capacity for crabs:

$$F_C(C, O) = r_C C \left[1 - \frac{C}{K_C \left(1 + \zeta \frac{O}{K_O} \right)} \right]$$

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The parameters r_C and K_C represent for blue crabs' intrinsic growth rate and carrying capacity respectively, while ζ represents the percentage increase in the crabs' carrying capacity with an increase in Bay's aggregate stock, relative to its own carrying capacity.

The value of clean water is difficult to parameterize, because of the difficulties associated with the measurement of all relevant values (Cropper and Isaac, 2011; Newcome et al., 2005). Fortunately, because the optimal solution sets $N = N^*$ at all points in time, we do not need to know the shape of $U(N)$ for other values of N. We assume that the optimal singular solution for N, N^* is known. We set N^* equal to the equilibrium level of nitrogen that would occur in the Bay, if nitrogen loadings were equal to the TMDL target level of 185.9 million pounds per year (EPA, Chesapeake Bay TMDL, Executive Summary). We do need to know the value of $U(N^*)$ to calculate the social welfare function, though its specific value will not affect the optimal values of control variables.

Assigning a value for $U(N^*)$, and for the rest of the parameters, involved taking published values from the literature, calculations using different data sources and in some cases educated guesses based on expert judgment. Details on the selection of parameter values are provided in an Appendix. Table 1 summarizes all parameter values and their definitions. For all areas we impose the same initial condition on the oyster stock, equal to $\frac{v}{P_O q_O}$, which is the open access equilibrium stock level. Similarly, the initial stock for blue crabs is given by $\frac{m}{P_C q_C}$. Numerical simulations were conducted that followed all optimality and arbitrage conditions, as well as all state equations. Simulations are performed for 200 years with a time step of 0.1 years.

[Table 1 p.27]

Simulations were used to obtain the maximized net present value (NPV) of SW under different area allocations. We now turn to the specification of area allocation scenarios. Two broad cases are examined: 1) Oyster fishing effort in public grounds is optimally regulated and 2) the public grounds oyster fishery is in open access. While the first case utilizes all optimality and arbitrage conditions for the simulations, in the second we replace the oyster arbitrage condition with its bionomic equilibrium stock level and fishing effort is set to achieve this

outcome at all points in time. It is well known that the second case implies dissipation of rents in public oyster fishery.

For each case, ten scenarios are evaluated. In the first scenario, identified as the baseline, each of the four management regimes occupies one fourth of the Bay. Other scenarios represent different combinations of area allocations. Because our model of aquaculture economics is simplistic, all scenarios keep the area dedicated to aquaculture constant at 25% of the Bay. Table 2 lists the ten allocation scenarios evaluated for each case.

Table 2: Simulation Scenarios and NPV for each case

	Area Allocations (proportion)				NPV of SW ($ billions)	
	a_S	a_R	a_W	a_A	Optimal Effort	Open Access
Baseline	0.25	0.25	0.25	0.25	0	-2.63
Scenario 1	0.5	0.25	0	0.25	-1.75	-1.75
Scenario 2	0.5	0	0.25	0.25	-1.16	-3.82
Scenario 3	0.75	0	0	0.25	-3.13	-3.13
Scenario 4	0.25	0.5	0	0.25	-0.59	-0.59
Scenario 5	0	0.5	0.25	0.25	0.95	-1.64
Scenario 6	0	0.75	0	0.25	0.37	0.37
Scenario 7	0.25	0	0.5	0.25	0.59	-4.47
Scenario 8	0	0.25	0.5	0.25	1.56	-3.45
Scenario 9	0	0	0.75	0.25	2.15	-5.08

5. Simulation Results

Before discussing differences among scenarios, we first explore the characteristics of the optimal solution for the baseline scenarios. Specifically, we explore the timing of the harvest pulses in the reserve and the stock of oysters in public grounds.

Figure 1: Oyster stock dynamics in the Reserve

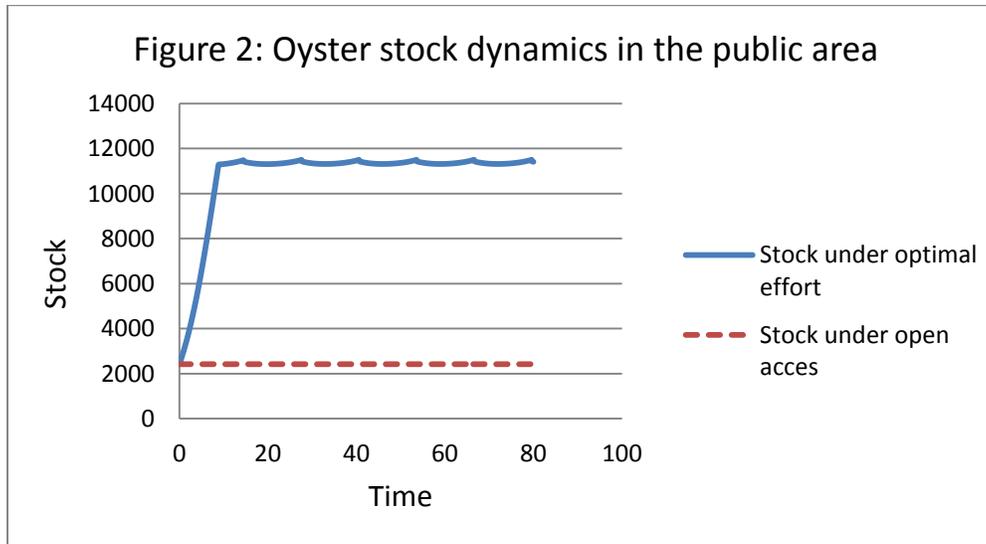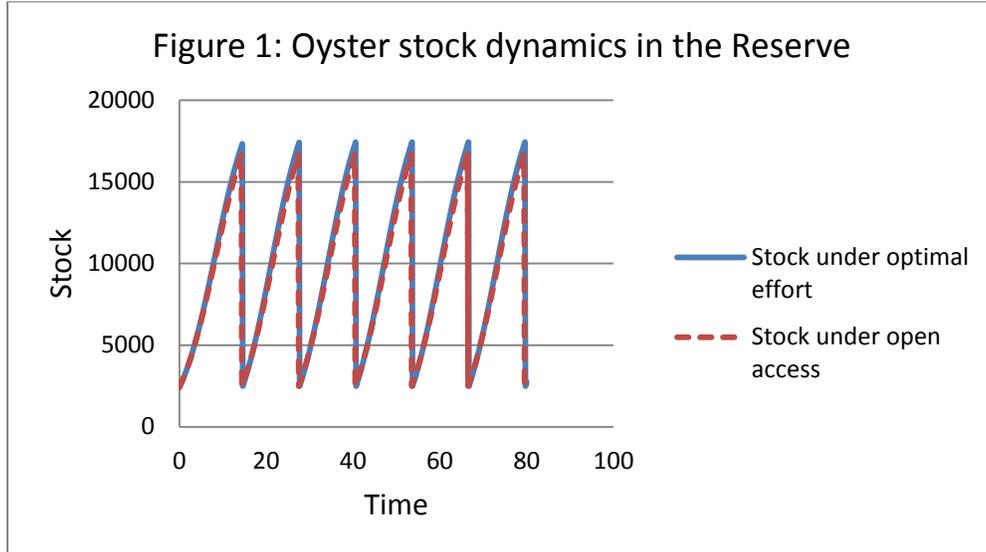Figure 2: Oyster stock dynamics in the public area

Figure 1 shows the stock dynamics in the reserve under each case. Under both regulated fishing effort and open access, the baseline simulation reveals that the optimal rotation length in the reserve is the same. It starts out at 14.5 years, but stabilizes at 13 years after the second cycle. The longer duration of the first cycle is because of the low initial stock imposed in all areas.

While the cycle lengths are the same under both cases, the oyster stock in the reserve reaches slightly higher levels when public ground effort is managed, because higher stocks in public grounds increase recruitment in the reserve.

Figure 2 shows the dynamics in public grounds. The stock fluctuates over each reserve cycle because of changes in recruitment and the harvest pulse that occurs in public grounds when the reserve is opened for harvest. When the public fishery is optimally regulated, the stock fluctuates around 11360 oysters per acre, whereas the corresponding figure for open access is 2400. It is this difference in stock in public grounds between the two cases, coupled with the stock spillover that yields higher stock in reserve under optimal fishing effort.

Before moving on, it is worth mentioning how the reserve rotation length and the singular solution of regulated public grounds would change if some key parameters were to change. For instance, a higher marginal cost of BMPs (the parameter l) would imply longer rotation lengths in the reserve. In addition, the stock in the reserve would reach higher levels, promoting greater singular solution for public oysters, due to the stock spillover. Intuitively, when the marginal cost of BMPs is high, the stock in the area should stay unharvested longer, allowing it to reach higher levels. Expensive BMPs would make denitrification more attractive. On the other hand, a higher denitrification rate (the parameter ρ) would imply shorter rotation lengths and smaller stock levels in the reserve. All other things constant, a higher rate of denitrification would incentivize more frequent harvests with a subsequent smaller stock spillover to public grounds. Lastly, a higher biodiversity spillover (the parameter ζ) would encourage longer rotation lengths in the reserve and greater singular stock in public grounds, due to the positive effect oysters have on crabs.

We now turn to directly address the research question of this paper, regarding the efficiency tradeoffs of having one management system versus a combination of them, or whether all regimes can coexist. As previously stated, our criterion of choice is maximization of NPV of the social welfare function. For each case, the NPVs of all scenarios are measured relative to the NPV of the optimally regulated baseline scenario[7]. Table 2 summarizes this information in billions of dollars, across all scenarios for both cases. Several findings are worth noting. First,

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[7] This results in the NPV of the optimally regulated baseline scenario to be equal to zero.

when fishing effort is regulated, NPV is maximized under the "corner solution" of having all available area dedicated to public grounds (scenario 9). This is the first-best outcome of the system. If, for other reasons, some portion of the Bay is to be protected from harvest as a sanctuary or a reserve, areas in reserves generate higher social welfare than areas in sanctuary (compare scenarios 5, 6 and 8 with 1-4).

The first set of results makes economic, as well as intuitive sense and they are in accordance with results found elsewhere. In particular, the largest NPV is obtained under scenarios 9 (first-best), 8 (second-best) and 5 respectively. These results indicate that sanctuaries should not be operated.

The general conclusion that in a deterministic environment, the existence of no-harvest zones is essentially needless if fishing effort can be perfectly and permanently controlled is also supported by other studies (Hannesson, 1998; Holland and Brazee, 1996; Holland, 2000; Anderson, 2002). In addition, the results highlight the efficiency gains of having as much public grounds as possible (scenario 9), followed by reserve (scenarios 5 and 8). This should come as no surprise, given the stream of income these regimes provide. On the one hand, the continuous harvest implied by the public oyster fishery unambiguously enhances local economy through income to watermen and employment opportunities to work in the fishery. On the other hand, the pulsed harvest in reserve also boosts fishermen's income, followed by a necessary period for the stock to rebound.

The results are different under open access in public grounds (second case). When there is no control on effort, devoting the entire area to public harvest is no longer the best outcome, but is actually the worst. NPV is maximized when the entire system is in the reserve (scenario 6). With the rents in public grounds being dissipated, the reserve is the only area that provides rents to oyster fishermen. Thus, the first-best solution is to allocate all available area to reserves. If some portion of the Bay is to be managed as a sanctuary or public fishery, sanctuaries generate higher social welfare than public grounds. In particular, scenario 4 can viewed as the second-best outcome of the system and entails shutting down public grounds and devote their area to the sanctuary. This result is of particular interest. It implies that if fishing effort cannot be controlled and we cannot achieve having the entire system in pulsed harvest, sanctuaries can play an important role, compared to public grounds. This is so because having some stock safely

protected generates value to society in terms of more blue crab harvests (through the biodiversity spillover) as well as greater cost savings in BMPs (due to nitrogen removal). Sanctuaries can serve this role because the stock that grows there does not disperse. Previous studies (Hannesson, 1998; Anderson, 2002) have shown that a high fish migration rate makes the protected area inefficient, since the stock is overharvested, but our results here indicate the opposite.

6. Discussion

This paper addresses the research question of the optimal combination of four management systems: sanctuaries, harvest reserves, aquaculture and public grounds, of a species that is sedentary as adults. Our bioeconomic model is for oysters in the Chesapeake Bay but it can be applied to any system that has no-harvest, pulsed and continuous harvest regimes. Incorporating stock, environmental and biodiversity externalities and using impulsive optimal control theory we examined the sensitivity of our results to two cases: optimal fishing effort and open access.

Results in both cases support the notion that it is not socially optimal for all four management systems to coexist simultaneously. We find that when effort can be managed, the system that generates the highest benefits is public oyster harvest in the entire area. This is the first-best outcome. When this outcome cannot be achieved, due to political or other reasons, and some portion of the system is to be managed as sanctuary or a reserve, the latter outperforms the first. This combination of public grounds and reserve constitutes the second-best outcome of the system. Under open access, the results favor operating the entire system in reserves. When this outcome cannot be attained, sanctuaries provide more public benefit than open access from public grounds.

In both cases, however, sanctuaries are never better than reserves. This particular result should not be surprising. A sanctuary can be thought of as a reserve with an infinitely long rotation interval. A reserve should always outperform a sanctuary, since the latter is a special case of the former. Even if the nitrogen removal benefits from having a large oyster stock were very large, or the improvement in crab productivity was very large, it would not be optimal to manage all areas as sanctuaries. Reserves would always do at least as well as sanctuaries, though the optimal rotation lengths of the reserves would tend to be longer in such cases.

Modeling complex economic-ecological systems like the Chesapeake Bay necessitates several simplifying assumptions. We discuss some of them in relation to our results here. First, the objective function of our model is linear in the choice variables, resulting in bang-bang controls. While solutions to such problems are relatively easy to derive, they may rely on restrictive assumptions. For example, the optimality rule for nitrogen implies that policy makers have the resources and the ability to achieve the nitrogen reductions necessary to meet TMDL goals. While the existence of such resources might be true, their implementation through BMPs and successful adoption by agents (e.g. farmers) is an empirical question. In addition, relative to the discussion about the choice of $U(N^*)$, it needs to be pointed out that the simulation NPV figures only serve the purpose of efficiency comparison among scenarios and do not provide measures of the total value to society generated by the resources. Although including what we call "utility from clean water" adds realism to our model, it also stresses the need for more research towards its more accurate estimation.

An important caveat is the simplistic way we model aquaculture. Given the dramatic decline of oyster stocks relative to its historic levels (Wilberg et al., 2011), we acknowledge the importance of aquaculture and allow a constant volume to be produced given its area allocation. However, from the brief description in section 2, it should be clear that the different types of aquaculture, along with the different regulatory approaches the states adopt, make this system more complicated. Because our model for aquaculture is simplistic, the results should not be used to evaluate whether aquaculture should be expanded or contracted in the Bay.

Our model allows oysters to have a positive effect on biodiversity, through their positive impact on blue crabs. Our simulations showed that, in the open access case, sanctuaries outperform public grounds. Part of the reason behind this result was the increased blue crab harvest through the biodiversity spillover that oyster stock in sanctuaries promotes. The positive association between the two species has profound policy implications, as regimes that support greater oyster stock are favored. This also justifies the decision to include a second species in the model, increasing its complexity. Nonetheless, it should be pointed out that the choice of blue crabs was primarily for their historic and commercial importance. The theory and simulation approach used here is applicable to other species, as long as they can be affected by oyster abundance.

The first-best outcome under the case where effort can be regulated supports having as much public grounds as possible. However, one should keep in mind that all economic decisions in our model are taken in a deterministic setting. Stochastic processes, such as disease, toxic algal blooms and freshets (CBP, 2004) and climate-change related phenomena could play an important role, calling for a combination of public fisheries with marine protected areas. Towards this possibility, the second-best outcome with public area and reserve is of real policy relevance. On the other hand, if regulatory agencies are not effective in controlling fishing effort and the public stock is overharvested; marine protected areas (reserves and sanctuaries, with the first being preferred) should be the focus of attention for policy making, regardless of uncertainty.

Our analysis captures only the two extremes: optimal effort regulation and open access in the public fishery. The first represents a strict, perfectly efficient and rather unrealistic institutional setting that has been extensively studied in many applications. The latter simply signifies complete absence of institutions. While pure open access has known and undesirable economic outcomes, marine protected areas come as an answer in an imperfect world, where policy makers acknowledge the political and economic difficulties of perfectly and permanently controlling effort (Sanchirico and Wilen, 2001).

Our approach assumes only one reserve, which is harvested at discrete points in time. In practice, there will be many different reserve areas, each of which will be opened at different times. This would imply the harvest from reserves would be less lumpy over time than modeled here, and jumps in other state variables (crabs, oysters in the public grounds, and nitrogen) will be smaller.

Finally, we point out that our model ignores restoration activities that typically take place when a new sanctuary is created. If those restoration activities, which can include reef creation, increase the future productivity of that area, then there may be a more important role for sanctuaries to play. Further, some parts of the Bay may be better suited to different management regimes, due to differences in salinity or bottom conditions. However, to analyze such a situation would require a model that relaxes the area-homogeneity assumption.

Table 1. Parameter Values

Symbol	Value	Definition
Biological Parameters		
$\overline{L}$	356,000,000	Long-run average annual loadings of N (in pounds)
ρ	0.001653	Denitrification rate (in pounds per market-sized oyster)
s	0.001146	N removal through harvest (in pounds per market-sized oyster)
d	0.9	Annual nitrogen decay
r_o	0.2	Oysters' intrinsic growth rate
K_O	18935.64	Per acre oysters' carrying capacity
φ	0.034	Stock spillover from larvae dispersal
r_C	0.52	Blue crabs' intrinsic growth rate
K_C	550,000,000	Blue crabs' carrying capacity
ζ	0.3	Biodiversity spillover
$N(0)$	250,497,792	Initial condition for N (in pounds)
N^*	200,000,000	N in the Bay implied by TMDL load target (in pounds)
Economic Parameters		
δ	0.03	Discount rate
a_{BAY}	637197.2	Total amount of quality oyster habitat in Bay (in acres)
P_O	0.5	Unit price of market-sized oyster
v	186	Cost per acre per unit effort in oyster harvest
q_O	0.153830645	Catchability coefficient for oysters
P_C	0.3	Unit price of age-1+ blue crab
m	305	Cost per unit effort in blue crab harvest
q_C	2.88917E-05	Catchability coefficient for blue crabs
y	0.000131579	Cost parameter for aquaculture
l	5	Cost per pound of N reduced through BMPs
$U(N^*)$	3,500,000,000	Value of clean water for achieving N TMDL target

Mathematical Appendix

Differentiating (6) with respect to time and keeping in mind that $\dot{\lambda}_N = 0$ yields

$$\dot{\lambda}_P = a_P \frac{v\dot{O}_P}{q_O O_P^2}$$

Given the state equation $\dot{O}_P = F(O_P) + I(O) - q_O E_P O_P$ we get

$$\dot{\lambda}_P = a_P \frac{v}{q_O O_P^2}[F(O_P) + I(O) - q_O E_P O_P]$$

Substituting λ_P from (6) into (7) and simplifying we get

$$\dot{\lambda}_P = \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right][\delta - F'(O_P)] - \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R) - \frac{\partial I}{\partial O_P}\left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right]$$

$$- a_P \frac{v E_P}{O_P} - \lambda_C \frac{\partial F_C}{\partial O_P} + a_P \rho \lambda_N$$

Equating the RHS of expressions with $\dot{\lambda}_W$ yields

$$a_P \frac{v}{q_O O_P^2}[F(O_P) + I(O) - q_O E_P O_P]$$

$$= \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right][\delta - F'(O_P)] - \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R)$$

$$- \frac{\partial I}{\partial O_P}\left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right] - a_P \frac{v E_P}{O_P} - \lambda_C \frac{\partial F_C}{\partial O_P} + a_P \rho \lambda_N$$

$$a_P \frac{v}{q_O O_P^2}[F(O_P) + I(O)] - a_P \frac{v q_O E_P O_P}{q_O O_P^2}$$

$$= \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right][\delta - F'(O_P)] - \frac{\partial I}{\partial O_P}(\lambda_S + \lambda_R)$$

$$- \frac{\partial I}{\partial O_P}\left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N\right] - a_P \frac{v E_P}{O_P} - \lambda_C \frac{\partial F_C}{\partial O_P} + a_P \rho \lambda_N$$

The terms $a_P \frac{v q_O E_P O_P}{q_O O_P^2}$ and $a_P \frac{v E_P}{O_P}$ are cancel out so that

$$a_P \frac{v}{q_O O_P^2} [F(O_P) + I(O)]$$

$$= \delta \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right] - F'(O_P) \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right]$$

$$- \frac{\partial I}{\partial O_P} (\lambda_S + \lambda_R) - \frac{\partial I}{\partial O_P} \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right] - \lambda_C \frac{\partial F_C}{\partial O_P} + a_P \rho \lambda_N$$

$$\delta \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right]$$

$$= F'(O_P) \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right] + \frac{\partial I}{\partial O_P} \left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right]$$

$$+ \frac{v}{q_O O_P^2} [F(O_P) + I(O)] + \left\{ \frac{\partial I}{\partial O_P} (\lambda_S + \lambda_R) + \lambda_C \frac{\partial F_C}{\partial O_P} - a_P \rho \lambda_N \right\}$$

Dividing through by $\left[P_O a_P - \frac{a_P v}{q_O O_P} - a_P s \lambda_N \right]$ we get

$$\delta = \left[F'(O_P) + \frac{\partial I}{\partial O_P} \right] + \frac{v}{O_P (P_O q_O O_P - v - s \lambda_N q_O O_P)} [F(O_P) + I(O)]$$

$$+ \frac{q_O O_W}{a_P (P_O q_O O_P - v - s \lambda_N q_O O_P)} \left\{ \frac{\partial I}{\partial O_P} (\lambda_S + \lambda_R) + \lambda_C \frac{\partial F_C}{\partial O_P} - a_P \rho \lambda_N \right\}$$

which is equation (11).

Parameterization Appendix

1. <u>Biological Parameters</u>

- a_{MD} = total amount of quality oyster habitat in Maryland measured in acres. This figure is not a biological parameter and it is not illustrated at Table 1, but will be used bellow for the calculation of carrying capacity. Michalel D. Naylor (pers. communication) provided us with the acres devoted to public harvest (27360), sanctuaries (239,700), reserves (1517) and aggregate aquaculture (4419) for the state of Maryland. The last figure represents acres used in private leased aquaculture for both clams and oysters and therefore cannot be used as it is. Accurate figures regarding acres devoted and harvest for oyster aquaculture in Maryland are not available. Nonetheless, for Virginia average harvest for the period 2005-2010 could be easily calculated for both aquacultured oysters (8 million per year) and jointly for clams and oysters (190 million) (Murray and Hudson, 2011), yielding the ratio of oysters to joint harvest equal to 0.042105. Therefore, for each state, the acres devoted to oyster aquaculture could be recovered using the following formula:

$$\frac{\#of\ oysters\ harvested}{\#of\ oysters+clams\ harvested} * acres\ devoted\ to\ joint\ aquaculture.$$

  Applying the same harvest ratio for Maryland and using the associated acres for joint aquaculture, the area devoted to privately leased oystering was found to be 186.0632 acres. Therefore $a_{MD} = 27360 + 239,700 + 1517 + 186.0632 = 268763.0632$

- $\bar{L}$ = nitrogen loadings in pounds and includes point, non-point, urban runoff and atmospheric deposition. It does not include tidal loads. 356 million pounds is the long-run average load per year of N reached the Bay from 1990-2010 (CBP). Sources of 1990-2010 are: 1) River input measured load (58%) (from the 9 mouth river stations accounting for 78% of the mean annual streamflow to the Bay), 2)Wastewater downstream of monitoring (13%), 3) Nonpoint sources downstream of monitoring (23%), 4) Atmospheric deposition to tidal waters (6%) (U.S. G. S, Table 2.)

- ρ = pounds per year of N removed from 1 g DW (gram dry weight) oyster or, equivalently, from 1 adult oyster of 3 inches, which is 0.75 g of N under natural feeding conditions in Choptank River (Newell, 2004; Newell et al., 2005). The figure in Table 1 is 0.75 g of N converted in pounds.

- s = pounds of N removed per adult harvested oyster, which contains 0.52 g of N (Newell, 2004; Newell et al., 2005) Both s and ρ estimates did not take into account the reduced levels of N removal of oysters under 3 inches, nor the increased removal of oysters over 3 inches. The calculations apply for the mid-Bay mesohaline (medium

salinity) region close to Choptank River, for adult oysters of exactly 3 inches long. The figure in Table 1 is 0.52 g of N converted in pounds.

- d = nitrogen decay excluding nitrogen removal through harvest and denitrification. This is a percentage of total nitrogen in the system and it is unitless. Similar to Smith and Crowder (2011), we use personal judgment and consider the natural decay of N large (close to 1) and rapid. The figure adopted for the instantaneous rate of nitrogen decay is 0.90.

- K_O = carrying capacity measured as number of adult, market-sized oysters per acre. Both Maryland and Virginia are assumed to have the same carrying capacity. The figure for Maryland is 5,089,200,000 oysters as of 2004. Jordan and Croakley (2004) estimated this figure and brief description of assumptions and procedures taken can be found in Wieland and Kasperski (2008 p. 15). Dividing with a_{MD}, we yield the 'per acre' figure for carrying capacity illustrated in Table 1.

- r_o = intrinsic growth rate. To calculate Bay's intrinsic growth rate, time series data for harvest, stock abundance and natural disease mortality were obtained. Oyster abundance data for both market-sized and small oysters were collected from Virginia Institute of Marine Sciences data base (VIMS) concerning both Maryland and Virginia. The estimated figures are for basin estimates and for Maryland they span from 1994-2001, while for Virginia from 1994-2007. For the years the two datasets overlapped the percentage of Maryland's stock relatively to Virginia was calculated. It was found that the combined stock (both small and market-sized) of Maryland was 27.33% of its Virginia counterpart.

  Harvest data for market-sized oysters for the period 1994-2007 were taken from Kasperski and Wieland (2009). For the same period data on oyster bushels harvested in Virginia was obtained (VIMS) and were transformed into market-sized figures using the conversion of 350 adult oysters per Virginia bushel. The two harvest figures from Maryland and Virginia were combined to yield a Bay-wide time series of market-sized oysters from 1994-2007.

  The next step was to calculate Bay's market-sized oyster abundance estimate. For this, only data for Maryland were available and taken from Kasperski and Wieland (2009). The associated figure for Virginia was obtained using the percentage of Marylands' combined stock relative to Virginia (27.33% presented above) and divide Maryland market-sized figure with that. The summation of the two adult oyster figures yielded a Bay-wide time series of oyster abundance.

  In order to calculate the intrinsic growth rate, the percentage of natural disease mortality was obtained. For Maryland we used again the figures from Kasperski and Wieland (2009). Because, to the best of our knowledge, there is not a uniform disease mortality percentage figure for Virginia's part of the Bay, we used the fixed 50% figure from Carnegie and Eugene (2011) that reflects approximate mean annual mortality in York

River. For each year between 1994 and 2007 the Bay's average percent of disease mortality was calculated.

Having all the necessary data we calculated Bay's intrinsic growth rate for market sized oysters using the same technique with Wieland and Kasperski (2008) and Kasperski and Wieland (2009). In particular, net recruitment (NR_t) was calculated as $NR_t = (Stock_t - Stock_{t-1}) + (1 - Dis.Mort_t) * Harvest_t$. Then the net recruitment ratio (NRR_t) was calculated as $NRR_t = NR_t/Stock_{t-1}$. Similar to Kasperski and Wieland (2009) the intrinsic growth rate was calculated as the average of those years, where NRR_t was positive and found $r = 0.1978 \approx 0.2$.

- φ = stock spillover, measured as the percentage increase in an area's oysters per acre attributed to larvae dispersal from Bay's aggregate stock. Finding a single estimate for this parameter is not an easy task. We referred to the sophisticated hydrodynamic model by North and colleagues (2008), who simulated larvae (referred to as particles in the paper) dispersal, while keeping track of their initial location and final settlement. Circulation patterns were also taken into account in the paper. Among others, the authors found an *annual transport success* for the entire Bay equal to 68%. Transport success is defined as the number of larvae that encountered (and settled to) an oyster bar per number of released larvae from the whole Bay (North et al., 2008). Nonetheless, the release of larvae was more of a computational artifact (for simulation purposes) rather than modeled through actual gamete (eggs and sperm) production. Moreover, larval growth and mortality were held constant for the purposes of the study. Larval mortality was the only process addressed in the paper, occurring if larvae could not encounter suitable habitat, and calculated as being 32%. For the calculation of φ, clearly some better measure of larvae mortality should be used. North (pers. communication) pointed out that low salinity, predation, poor growth and disease are all very important factors to larvae mortality accounting for way more than 65%. We therefore used the planktonic larvae mortality of 95% found in Eckman (1996). The spillover effect for the Bay was calculated as $\varphi = Annual\ transport\ success * [1 - larvae\ mortality]$ and found to be 0.034 (or 3.4%).

- ζ = biodiversity spillover, representing the percentage increase in blue crab's carrying capacity attributed to increases in Bay's aggregate oyster stock per acre relative to its own carrying capacity. Parameterization of ζ is another difficult tusk given the multi-feeding behavior of blue crabs, coupled with the complex migration patterns of the species. Harding and Mann (2010) studied whether an oyster reef, oyster bar or a sand bar have different effects on blue crab abundance in Piankatank River, VA between 1996 and 1997. Crab abundance is measured by harvests using the commercial crab pot as the sampling unit. In their study Catch Per Unit Effort (CPUE) is the comparison statistic defined as crabs per pot per day. Among the results is that both oyster reef and bar had greater average total daily CPUE. However, the observed results may be attributed to differences in depth, tidal current, associated food resources other than oysters and the like (Harding and Mann, 2010). More importantly, the effect of oyster reef and bar on CPUE was very small due to the local scale of the study (6.74 and 9.16 average total daily CPUE), was measured in quantities (rather than percentage) and does not provide a

direct effect of oyster abundance on crabs' enhanced growth. Nonetheless, the authors support that "*efforts to rebuild natural oyster population and the biogenic structure offered by either natural bars or three dimensional reefs will provide inherent habitat to crab populations given the dual enhancement of the forage base and habitat heterogeneity provided by biogenic oyster habitats* (Harding and Mann, 2010 p. 88)".

Mesocosm trials (Van Mort Frans et al., 2003) examined responses of last stage larvae and first juvenile blue crabs on six different substrates, among which live oysters C. Virginica was one. The six substrates were separated, each one containing equal initial number of crabs. Total access after acclimation was allowed in order to test the null hypothesis of equal distribution among substrates after 13 hours (Van Mort Frans et al., 2003). Even though 35% of the total last stage larvae crabs were recovered from the eel grass (*Zostera Marina*), 30% of the total first juvenile crabs were found in oysters quantifying a significant preference of juvenile crabs on the species. The field experiment revealed overnight settlement of blue crabs on oysters of 27% and even though less than the ell grass, it was significantly higher compared to mud (18%). Clearly both quantitative and qualitative results, regarding both substrate effects on blue crab abundance and settlement preference of juveniles the substrate, do not reflect direct enhancement of crab growth attributed to increased market-sized oyster's abundance. For the purposes of this study, we use personal judgment and set ζ equal to 0.3 (or 30%).

- r_C = intrinsic growth rate of adult blue crabs age-1+, which are those considered mature and ready to spawn. Data from 2012 Blue Crab Advisory Report (Chesapeake Bay Program), for the years 1990-2009 were obtained. The data, among others contained the estimated abundance of adult age-1+ blue crabs (in millions), along with the annual percentage of them harvested. Having the estimated abundance of adult-age+ crabs and the annual percentage harvested, we calculated the actual harvest figure in millions for each year. In addition, we adopted the constant natural mortality rate found in the paper by Rugolo and colleagues (1998) of 37.5% per year. Using the same approach with Wieland and Kasperski (2008) and Kasperski and Wieland (2009) (see r_o parameter above), r_C was found to be 0.52.

- K_C = Carrying capacity in millions for the Blue crabs of age-1+. The 2011 stock assessment (Miller et al., 2011) and one of the authors (Miller, per. communication) suggest that about 275 million female crabs are equivalent to a zero catch. Upon assuming a 50:50 sex ratio, that would yield approximately 550 million of age-1+ crabs. The last figure is the one used for this paper.

2. <u>Economic Parameters</u>

- δ = discount rate. Using personal judgment we adopt the conventional discount rate of 0.03 or 3%.

- q_C = catchability coefficient for blue crabs. For the calculation of this parameter, stock abundance and harvest data for market-sized blue crabs were necessary. Therefore, we restricted our attention to spawning-age crabs including both males and females. Table 3 from the 2012 Chesapeake Bay Blue Crab Advisory Report (Chesapeake Bay Program), provided stock abundance in millions, and the percentage harvested, from where harvest was calculated. For the period 1990-2006 the average abundance and harvest were found to be 190.066 and 97.991 million respectively. As a measure of effort we used the boat-days found in Wieland (2007), which yield an average of 17844.705 for the period 1990-2006. The catchability coefficient was calculated as $q_C = \frac{H_C}{E_C C}$ and it is provided in Table 1.

- m = unit cost of crab effort. As we were informed by Lipton (pers. communication) the only study that could provide some insights about the unit cost of crab effort is the one by Rhodes and colleagues (2001). The authors surveyed 2,999 watermen by mail, with 1,406 returned for the year 1999. The average crab-fishing days per season, for full-time watermen, were 81.4 for Maryland and 83.6 for Virginia respectively. This yielded a Bay average of 83 crab-fishing days per season. The authors broke up the costs of crabbing as fixed ones (incurred regardless of crabbing) and variable (incurred only if harvest takes place) (Rhodes et al., 2001) The former includes boat and engine maintenance, boat insurance, docking, license fees and boat depreciation. The latter incorporates gear, bait, fuel and labor. The authors calculated an average total cost per day of $228 for Maryland and $279 for Virginia respectively, yielding an average total cost per day for full-time crab employment in the Bay of $253.5 \approx 254$. To be consistent with the time period used for calculation of q_C, the above figure, using the CPI, was converted into 2006 dollars yielding the figure at Table 1.

- P_o price per unit of market-sized oyster. The vast majority of agencies and online sources report harvest in pounds of oyster meat or bushels, along with the associated revenues from where oyster price can be recovered. However, the conversion of pounds and/or bushels to actual numbers is not straightforward because the two states use different metrics (e.g. 1 Virginia bushel is approximately 350 oysters, but different in Maryland). For the purposes of this study we used the report by Murray and Hudson (2011) and personal judgment. In the report the price per market-sized aquacultured oyster in Virginia is reported for the period 2005-2010 yielding an average of approximately $0.3. However, oysters are by far less abundant in public grounds and it is logical to assume increased costs, yielding higher dock prices compared to aquaculture. We therefore adopt the fixed price of $0.5 per adult harvested oyster.

- P_C price per unit of blue crab. Annual data from the National Ocean Economics Program were obtained for both Maryland and Virginia regarding landings in pounds as well as their value in dollars. The data spanned from 1999-2010 and the price per pound in all years were higher in Maryland than in Virginia with the average difference between the two states being $0.35. The average price per pound for the entire Bay was calculated as $0.91 and compared with the average for the Mid-Atlantic region for the same years, which was calculated as $0.96. The calculated bi-state average and the average for the Mid-Atlantic region were pretty close and therefore considered to capture pretty well the average price per pound in the region. For this study we use the figure of $0.91/pound. To convert the above figure into unit price, we used the conversion factors of Miller (2001). In particular for peeler/soft crabs the conversion is 0.2083 pounds per crab and for hard ones it is 0.35 pounds per crab. We use for convenience the figure of 0.33 pounds per crab, so that 1 pound is approximately 3 age-1+ crabs. The resulting price per unit of adult crab is calculated as $0.30.

- y = cost parameter in oyster aquaculture. Maximizing the aquaculture rent equation with respect to H_A and solving for the cost parameter we yield $= \frac{P_O}{2H_A}$. H_A represents aggregate harvest (from both Maryland and Virginia) of aquacultured oysters per acre. For the calculation of the cost parameter we therefore need harvest of aquacultured oysters in Maryland and total acreage available for the economic activity. Using the same formula for the calculation of acres available to Maryland's aquaculture described above, and the fact that 100,000 acres are available for joint aquaculture (both clams and oysters) in Virginia (Murray, and Hudson, 2011), the corresponding figure for acres devoted to oyster aquaculture in Virginia was found to be 4210.526. That yields $a_A^{BAY} = 4210.526 + 186.0632 = 4396.589$ where a_A^{BAY} stands for total acres devoted for oyster aquaculture in the entire Bay. Next, since 4210.526 acres in Virginia produce the average 8 million oysters for the period 2005-2010 (Murray, and Hudson, 2011), we can calculate what is the corresponding harvest of aquacultured oysters in Maryland associated with 186.0632 acres. Having Bay's total harvest in oyster aquaculture and total acres for this economic activity, applying the formula for y to obtain the figure in Table 1 is straightforward.

- v unit cost of oyster effort. This parameter was taken from Wieland's report describing operating costs in Chesapeake Bay oyster fishery based on a 2005 survey (Wieland, 2008b). The report assumes a 260 day work per year, from which oyster harvest constitutes about 100. Therefore all annual figures reported were divided by 100 in order to yield daily cost estimates. Both estimated docking costs and the cost of membership fees generated a daily figure of $4.61 ($461 per year). License and surcharge costs were $3.5 per day yielding a daily figure of "total other daily costs" of $8.11. Accounting for motor and drive train maintenance costs the author calculated a total daily figure regarding variable costs (defined as variable, but occurring regardless of oyster harvest) of approximately $10 per day. Turning to 'pure' variable costs these include a) fuel, b) harvest gear maintenance and repair costs and c) the opportunity cost of time. Based on the figures provided by Wieland (2008b) we calculated total effort dependent costs of $176 per day. Therefore, ignoring the purchasing price and depreciation cost of the boat

(these are fixed costs) the combined figure for variable effort-independent and effort-dependent daily cost was $186.

- q_o catchability coefficient for oysters. The parameter covers both harvesting at public grounds, as well as at reserves. For simplicity we ignore, the regulatory requirement regarding patent or hand tong during pulse in the reserve. As before, we calculate the parameter for Maryland and assume the same for Virginia. Market-sized oyster abundance and harvest in millions were obtained from Kasperski and Wieland (2009) for the period 1994-2007 and the corresponding averages were calculated. Average abundance and harvest were converted in 'per acre' figures, using the acres available for public oyster harvest (27,360) provided by Michael D. Naylor (pers. communication). As a measure of effort we used the number of boat-days found in Wieland (2007) and for the period 1994-2007 we converted the corresponding average in 'per acre' term as before. Catchability coefficient was calculated using the following expression:

$$q_o = \frac{oyster\ harvest\ per\ acre}{(oyster\ abundance\ per\ acre * boatdays\ per\ acre)}$$

- l marginal cost (per pound) of nitrogen removed through BMPs. The corresponding figure is $5 per pound of nitrogen removed taken from Nelson (2005).

3. Other parameters and initial values

- a_{BAY} total amount of quality oyster habitat. We already have the relevant figure for Maryland. For Virginia however, we only have acres devoted to public harvest and aquaculture and no figures regarding sanctuaries or reserves were available. For total oyster quality habitat for Virginia, we used the figure of 1491 Km^2 (368,434 in acres) taken from the report by Cerco and Noel (2006). This figure represents amount of area devoted to quality habitat and leased grounds, and along with the total oyster area in Maryland yields the figure presented in Table 1.

- $N(0)$ initial condition for nitrogen in the Bay, measured in pounds of the pollutant. In order to initialize nitrogen, data about concentrations and loads of the pollutant were collected from Chesapeake Bay River Input Monitoring Program regarding the largest rivers in the region, namely Susquehanna, Potomac, Patuxent, Choptank, Rappahannock and James (USGS). For Rappahannock and James the latest concentrations, measured in mg/L, were available for September 2010[8]. As for the remaining rivers, the latest data were available for January 2011[9]. To come up with a 2010-11 average nitrogen concentration for the Bay, we chose to weight the observed concentrations. To do so, 2010 loads, measured in kg/year and converted into pounds/year were obtained for each river. A weight for a particular river was calculated as its 2010 load divided by the total. Then the weighted average concentration (in mg/L) was calculated using the nitrogen

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[8] In particular September 29 and 30 for James and Rappahannock respectively were the dates, nitrogen concentration data were collected.

[9] In particular January 6 was the data-collection date for both Susquehanna and Potomac and January 5 and 10 for Patuxent and Choptank respectively.

concentrations described above. The resulting figure was converted in pounds per liter. In order to calculate the 2010-2011 concentration of nitrogen in pounds in the Bay, the next step was to figure out approximately how many liters of water there are in the estuary. Chesapeake Bay Program reports that there are more than 18 trillion gallons of water in the Bay (CBP: Facts and figures) and it was therefore straightforward to convert this number into liters. Multiplying the resulting figure with the weighted average concentration (in pounds per liter), we found the initial concentration of nitrogen in the Bay (reported in Table 1.), measured in pounds.

- N^* optimal amount of nitrogen in the Bay, measured in pounds, associated with achievement of the TMDL goal. As briefly mentioned in section 5, we used the state equation for nitrogen and replaced $\bar{L}$ with the nitrogen TMDL loadings target. The variable R (amount of nitrogen removed through BMPs) we not included since TMDL loadings are the final outcome we are interested to simulate for the calibration of N^*. Using the parameters ρ, a_{BAY}, s and d described above, and for average figures of oyster abundance and harvest in the Bay (O, H_O) taken from Wieland and Kasperski (2008) and Kasperski and Wieland (2009), we simulated the nitrogen state equation and found the equilibrium level of nitrogen in the Bay associated with the TMDL nitrogen loadings goal. This figure is reported at Table 1.

- $U(N^*)$ The choice of a numerical value for $U(N^*)$ was a challenging task. It captures all benefits relating to the achievement of nitrogen TMDL target including impacts on property values, on other commercial fisheries[10], on several recreational activities including fishing, swimming and boating, as well as on nonuse values. There is a considerable amount of literature estimating many of these benefits for the Bay over the years, and a comprehensive discussion of assumptions, techniques, results and limitations is presented in Cropper and Isaac (2011). Among the difficulties pointed out in the report, mapping nitrogen reductions into observed environmental outcomes, as well as issues related to the accurate measurement of nonuse values are among the most serious ones. In particular, properly measuring nonuse values is extremely difficult, if not impossible, due to stewardship, altruistic, bequest and existence values involved (Newcome et al., 2005). Therefore, $U(N^*)$ is most likely to be underestimated and to the best of our knowledge there is no study reporting a numerical value for it. The study by Morgan and Owens (2001) synthesizes some of the findings reported in Cropper and Isaac (2011) and attempts to provide an estimate of water quality benefits associated with nutrient water quality legislations in the Bay for the period 1972-1996. For the District of Columbia and portions of Maryland and Virginia monetary annual benefits for boating, fishing and swimming range from 357.9 million to 1.8 billion in 1996 dollars. The corresponding 2011 figures are \$487.7 million and \$2.45 billion respectively. Due to the limiting geographic coverage of the study, in relation to the entire watershed, and the fact that boating, fishing and swimming constitute only a subset of the benefits described in Cropper and Isaac (2011), we use personal judgment and choose the figure of \$3.5 billion per year for the Bay. Given that Bay's watershed population as of 2011 was 17.5 million

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[10] Apart from harvesting oysters and blue crabs.

(CBP), the chosen figure generates the plausible value of $200 in per capita use and non-use benefits.

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