ABSTRACT

MILLSTEIN, ERIKA SHIELDS. Oyster Reef Restoration as a Fisheries Management Tool. (Under the direction of David B. Eggleston).

Global declines in fish stocks over the past several decades have been caused by a combination of factors, including overfishing, habitat destruction, and water quality degradation. Despite the complexity of the problem, fisheries management traditionally focuses on effort reductions for individual fish stocks to rebuild populations. This single species management approach is often unsuccessful. Habitat restoration, however, is rarely included in management strategies and few studies have addressed the effectiveness of habitat restoration as a fisheries management tool. In the coastal southeast United States, the eastern oyster, *Crassostrea virginica* is an economically and ecologically important species. Oysters act as ecosystem engineers by building structurally dynamic reefs, providing habitat, cycling nutrients, and filtering water, thereby increasing water clarity. Oyster population declines have motivated state agencies, academic institutions, and local communities to initiate oyster reef habitat restoration projects. In addition to augmenting oyster populations, the restored reefs also provide essential habitat for a variety of economically and ecologically important fish and shellfish including black sea bass (*Centropristis striata*), gag grouper (*Mycteroperca microlepis*), sheepshead (*Archosargus probatocephalus*), gray snapper (*Lutjanus griseus*), and stone crab (*Menippe mercenaria*). The potential for restored oyster

reefs to enhance the abundance and population growth rate of reef associated fish, and thereby offset catch reduction, has not been fully examined.

This research assessed the biological and economic effectiveness of oyster restoration as a fisheries management tool for black sea bass. We hypothesize that: (H_1) population growth rate of black sea bass will increase with increasing oyster reef area; and (H_2) that the extent of oyster reef necessary to reach a stable population growth rate for black sea bass would be greater than the current area of restored reef in the Southeast United States. We used a computer simulation model to examine the black sea bass population growth rate response to oyster reef restoration, and to assess the economic costs and benefits of oyster reef restoration, fishing mortality reduction, and management inaction. The population growth rate of black sea bass increased with increasing oyster reef area; a total of 52.166 km^2 of oyster reef was necessary to stabilize the population growth rate of black sea bass and thereby offset fishing mortality reduction to the fishery. When the economic benefits of black sea bass, gag grouper, gray snapper, sheepshead and stone crab recreational and commercial fishing were included, oyster reef restoration was the most economically effective management option evaluated compared to fishing mortality reduction or management inactions. These results suggest that the habitat restoration is an economically effective, holistic management option for rebuilding fish populations.

Oyster Reef Restoration as a Fisheries Management Tool.

by
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BIOGRAPHY

Erika Shields Millstein was born on December 2, 1983 in Hartford, Connecticut, and grew up in nearby Simsbury, Connecticut. After graduating from Simsbury High School in 2002, Erika attended Bates College in Lewiston, Maine. During her Bates experience, Erika worked under Dr. William G. Ambrose researching relationships between global climate variation and artic clam growth, and studying the effects of commercial bait worm digging on intertidal mudflats in Maine. She spent time in Ecuador as a volunteer teacher, and was selected to conduct summer research internships in Qingdao, China, where she investigated inter-decadal variation in monsoon strength, and in Dauphin Island, Alabama, where she examined the effects of seagrass density on predator-prey relationships. Erika spent the final semester of her undergraduate education at the Duke Marine Lab before graduating from Bates Cum Laude with Honors in 2007. Between undergraduate and graduate school, Erika traveled to Perth, Australia, to research trophic preferences of marine gastropods. Erika has been working toward her Master's in Marine Science at North Carolina State University since fall 2007. She has enjoyed a variety of research experiences at NC State, including conducting a project assessing the timing of migration of mature female blue crabs in the White Oak River, and completing her thesis research addressing the efficacy of oyster reef restoration as a fisheries management tool. Erika now lives onboard S.V. Aqua Vitae, which will set sail for the Caribbean this fall.

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Background

Marine fisheries are an economically, nutritionally, and culturally important resource around the world. In 2004, marine capture fisheries produced 85.8 million tons, worth $84.9 billion in first time sales. In 2003 capture fisheries accounted for 15.5% of the world's animal protein production, and provided over 2.6 billion people with at least 20% of their animal protein (FAO Fisheries and Agriculture Department 2007). While marine fisheries provide a critically important protein source, global fisheries stocks have been declining over the last several decades, by some accounts drastically (Pauly et al. 1998). These declines have been caused by a combination of interrelated factors, including overfishing, habitat destruction, degraded water quality, and global climate change (Meyer et al.1997, Pauly et al. 1998, Jackson et al. 2001, Breitburg 2002). Despite the complexity of fisheries decline, traditional fisheries management often focuses on reducing fishing effort on a single species to rebuild populations.

The recent re-authorization of the Magnuson-Stevens Fishery Conservation and Management Act requires identification and conservation of essential fish habitat in fisheries management plans as a means to maintain viable fish populations (NOAA 2007). Habitat restoration, however, is rarely included in management strategies, and while studies have documented the importance of high quality habitat for fish and shellfish production (for example, Johnson et al. 1994, Zelder 2000, Peterson et al. 2003, Barbier et al. 2008), few studies have addressed its potential as a management tool.

In recognition of the importance of coastal and marine habitats for productive ecosystems, the National Oceanic and Atmospheric Administration (NOAA) Habitat Program funds habitat restoration initiatives, including the Community Based Restoration Program, whose goal is to restore fisheries habitat, and the Essential Fish Habitat Program, which identifies and describes essential fish habitat for federally managed species (NOAA Habitat Program). Empirical and modeling studies assessing the potential for particular habitats to serve as fisheries management tools would help the NOAA Habitat Program allocate funds for researching and restoring the most important habitats for fisheries production. The goal of this study is to assess the biological potential of habitat restoration as a fisheries management tool and to evaluate cost-effectiveness of such a project.

Oyster Reef Restoration

The eastern oyster, *Crassostrea virginica,* is an economically and ecologically important species. The states of the South Atlantic Fisheries Management Council (SAFMC), North Carolina, South Carolina, Georgia and Florida, landed nearly 1 million pounds of oysters, valued at more than $3 million in 2007 (NMFS 2007). Ecologically, oysters act as ecosystem engineers by building structurally dynamic reefs, providing habitat, and improving water quality via water filtration, nutrient cycling, and turbidity reduction (Lenihan et al. 2001).

The importance of this species and its declining abundance has motivated state agencies, academic institutions, and local communities to initiate oyster reef habitat restoration projects. For example, the North Carolina Division of Marine Fisheries

(NCDMF) has built no-take sub-tidal oyster reefs in the Pamlico Sound (NCDMF), and the University of Georgia's Marine Extension Service coordinates "Generating Enhanced Oyster Reefs in Georgia's Inshore Areas" to restore inter-tidal oyster reefs along Georgia's coast (UGA). Moreover, Maryland's Chesapeake Bay Program is a nonprofit organization restoring inter-tidal oyster reefs in the Chesapeake Bay (Chesapeake Bay Program). Restored oyster reefs are created by depositing cultch material, such as recycled and dredged oyster shells, clam and scallop shells, rocks, limestone chips, and crushed concrete, upon which larval oysters settle.

In addition to augmenting oyster populations, restored reefs provide habitat for a variety of commercially and recreationally important species, including black sea bass (*Centropristis striata*), gag grouper (*Mycteroperca microlepis*), sheepshead (*Archosargus probatocephalus*), gray snapper (*Lutjanus griseus*), and stone crab (*Menippe mercenaria*) (Peterson et al. 2003). Of these species, only black sea bass is currently overfished, and its population abundance has declined dramatically since the early 1970's (SEDAR 2005). While studies demonstrate oyster reefs are an important habitat for juvenile fishery species (Lenihan et al. 2001, Peterson *et al*. 2003), the potential for oyster reef habitat restoration to mitigate overfishing and rebuild populations such as black sea bass has not been addressed.

Objectives and Hypotheses

The goal of this research was to assess potential biological and economic effectiveness of oyster reef restoration as a fisheries management tool in the southeast United States over a 30 year period. Specifically, the objectives of this study were to (1) model and quantify the population growth rate response of black sea bass to oyster reef restoration; (2) evaluate the extent of reef habitat necessary to achieve a stable population growth rate of black sea bass; (3) develop a computer simulation model to estimate the economic costs versus benefits of oyster reef restoration compared to traditional fishing mortality reduction and management inaction for black sea bass management; and (4) assess the sensitivity of the model output to key model parameters.

We hypothesized that (H_1) population growth rate of black sea bass would increase with increased oyster reef area, and (H_2) the extent of reef necessary to reach a stable population growth rate of black sea bass would be greater than the current area of restored reef in the Southeast U.S.

Methods:

Model Species

Black sea bass (*Centropristis striata*), gag grouper (*Mycteroperca microlepis*), gray snapper (*Lutjanus griseus*), sheepshead (*Archosargus probatocephalus*), and stone crab (*Menippe mercenaria*) are commercially and recreationally important species whose young-of-the-year abundance and lifetime production are enhanced by the presence of oyster reef (Gwak 2003, Peterson et al. 2003). In studies comparing oyster reef to nearby soft sediment and seagrass habitats, species such as gag grouper, gray snapper, sheepshead and stone crab were found exclusively in the reef habitat. Black sea bass is found in both habitats, but is much more abundant on oyster reefs (Zimmerman et al. 1989, O'Beirn et al. 1999, Lenihan et al. 2001, Peterson et al. 2003). Furthermore, gut content analysis found that when black sea bass and oyster reef are co-located, sea bass rely heavily on the oyster reef ecosystems for food (O'Beirn et al. 1999). In addition, predation-induced juvenile black sea bass mortality was reduced in structurally complex habitats, such as oyster reefs, compared to sand (Scharf et al. 2006). Thus, oyster reefs are capable of enhancing production of certain fishery species by enhancing survival and possibly improving access to food resources.

Black sea bass, gag grouper, gray snapper, and stone crab are exploited by commercial and recreational fisheries in the U.S. South Atlantic. Black sea bass is currently the most heavily exploited of the five species, and recent assessments indicate that the South Atlantic population is both overfished and experiencing overfishing (NMFS 2009). A population is deemed overfished when the stock is exploited such that its abundance is considered too low for safe reproduction. A population experiences overfishing when it is exploited at a rate that jeopardizes the capacity of the stock to produce maximum sustainable yield, or the maximum catch that can continuously be taken from the stock under existing environmental conditions (NOAA Technical Memorandum 2005). Gag grouper is also heavily exploited, and while the stock is not currently overfished, its population size is approaching an overfished condition as a result of ongoing overfishing (NMFS 2008). While gray snapper is not currently experiencing overfishing, it is not known whether the population is overfished (NMFS 2008). The overall stock status of sheepshead and stone crab throughout the South Atlantic is not known, but Florida stock assessments indicate that neither sheepshead, nor stone crab is overfished or experiencing overfishing (Muller et al.

2006, Munyandorero et al. 2006). The Florida stone crab population, however, is currently harvested at its maximum sustainable yield, and the stock conditions would decline with additional fishing pressure under the current environmental conditions (Muller 2006).

Model Overview

There were three major steps in modeling oyster reef restoration as a black sea bass fisheries management tool. First, the population growth rate response of black sea bass to oyster restoration was modeled by estimating (i) demographic rates, (ii) fishing mortality and catch, and (iii) survival as a function of restored reef. From these estimates, we calculated (iv) the area of reef necessary to stabilize the sea bass population. Next, we evaluated the biological impact and subsequent economic benefits and costs of different fishery management strategies. We estimated (i) the catch of black sea bass and other species, and subsequent economic costs and benefits, in response to oyster restoration, (ii) the catch of black sea bass, and subsequent revenue, in response to reduced fishing mortality, (iii) the catch of black sea bass, and subsequent revenue, in response to management inaction, and (iv) the net economic benefits of all three management strategies (oyster restoration, catch reduction, inaction). Lastly, we conducted (i) sensitivity analyses of the estimated amount of reef necessary to stabilize the black sea bass population growth rate to variation in model inputs, such as fertility, survival, natural mortality, abundance, and assumed enhancement of sea bass abundance via reef restoration.

Uncertainty in future environmental conditions, especially those caused by climate change, limit the model period to 30 years. Moreover, black sea bass live 12 years (age-0 through age-11), and 18 12-year cohorts would complete their lifespan within the 30 year period, thereby allowing a sufficient number of generations to benefit from oyster restoration to assess the effects of reef restoration on the black sea bass population growth rate.

1. Population Growth Rate Response

The dominant eigenvalue (λ) of a population Leslie matrix (**L**) served as the proxy for the black sea bass population growth rate in this study. A Leslie matrix is a square matrix with age-specific fertility (f_i) along the top row, age-specific survival (s_i) on the diagonal, and all other elements equal to zero (Fig. 1). When $\lambda=1$, it indicates a stable population growth rate, whereas $\lambda<1$ indicates a declining population, and $\lambda>1$ indicates a growing population. A Leslie matrix predicts future age-specific abundance as:

$$\mathbf{n}_{(t+1)} = \mathbf{L}\mathbf{n}_{(t)} \tag{1}$$

where, $\mathbf{n}_{(t+1)}$ is a vector of age-specific abundance at time t+1, and $\mathbf{n}_{(t)}$ is a vector of age-specific abundance at time. For a 12 age-class model such as ours, $\mathbf{n}_{(t+1)}$ and $\mathbf{n}_{(t)}$ are 12x1 column vectors, and **L** is as 12x12 matrix (see Appendix 2 for a list of parameter symbols and definitions).

(i) Estimating Demographic Rates

Traditional Leslie matrix models rely on detailed biological studies to estimate survival and fertility rates (Caswell 2001). In the absence of reliable parameter estimates, quadratic programming can be used to estimate survival and fertility from a time-series of age-specific abundance of a given species (Wood 1994, Caswell 2001, Wielgus et al. 2007, 2008). In this case, we let **p** represent a column vector of the unknown, non-zero elements of the Leslie matrix, **L,** (Fig. 2a, Appendix 1) such that:

$$\mathbf{n}_{(t+1)} = (\mathbf{n}_{(t)} \otimes \mathbf{I}_{sxs})\mathbf{p} \tag{2}$$

where, $\mathbf{n}_{(t+1)}$ is a column vector (12x1, in our case) of age-specific abundance at time t+1, with length equal to the number of age- or stage-classes in the model; $\mathbf{n}_{(t)}$ is a column vector (12x1, in our case) of age-specific abundance at time t, with length equal to $\mathbf{n}_{(t+1)}$; $\mathbf{I}_{sxs}$ is an identity matrix (12x12, in our case) with dimensions equal to the dimensions of **L**; and **p** was a column vector (22x1, in our case, since age-0 fertility and age-11 survival equal 0) with length equal to the number of non-zero elements in **L**.

Let $\mathbf{Q}_0$ represent a row vector, formed by eliminating the columns of $(\mathbf{n}_{(t)} \otimes \mathbf{I}_{sxs})$ which correspond to the eliminated columns of **L**. The width of $\mathbf{Q}_0$ (1x22, in our case) equals the length of **p**. If we have an age-specific abundance time-series of length T, such that:

$$\begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{n}_T \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_0 \\ \mathbf{Q}_1 \\ \cdot \\ \cdot \\ \cdot \\ \mathbf{Q}_{T-1} \end{bmatrix} \mathbf{P} \tag{3}$$

then,

$$\mathbf{z} = \mathbf{Q}\mathbf{p} \tag{4}$$

where, **z** is a column vector (312x1, in our case) with length equal to the number of elements in the time series from year 2 through T and **Q** is a matrix (312x22, in our case) containing abundance data for year 2 through T-1, whose length equals the length of **z** and whose width equals the length of **p**. The vector **z** and matrix **Q** are known quantities, and the Leslie population matrix parameters can be estimated by solving the equation:

$$\underset{\mathbf{p}}{\textbf{minimize}} \ \| \mathbf{z} - \mathbf{Q}\mathbf{p} \|^2 \tag{5}$$

where, all parameters were described above. The solutions may be linearly constrained, and the problem can be solved by MATLAB's quadprog function (MATLAB 7.7.0; Caswell 2001).

In this model, there were 12 black sea bass age-classes, age-0 through age-11. The black sea bass age-0 through age-10 survival (age-11 survival is always 0) and age-1 through age-11 fertility (age-0 fertility is always 0) parameters were estimated from the age-specific abundance for the time period 1978-2004 (SEDAR 2005) using MATLAB's quadprog routine. All parameters were linearly constrained to the following biologically reasonable, non-negative values via the linear inequality (Table 1; Caswell 2001; Appendix 1):

(6) $$\mathbf{Ap} \leq \mathbf{b}$$

$$0 \leq s_{0\rightarrow 10} \leq 1$$
$$0 \leq f_1 \leq 3.9277$$
$$0 \leq f_2 \leq 6.7923$$
$$0 \leq f_3 \leq 7.2950$$
$$0 \leq f_4 \leq 5.3842$$
$$0 \leq f_5 \leq 2.2906$$
$$0 \leq f_6 \leq 1.4028$$
$$0 \leq f_7 \leq 1.1866$$
$$0 \leq f_8 \leq 0.2429$$
$$0 \leq f_9 \leq 0.1141$$
$$0 \leq f_{10} \leq 0.0410$$
$$0 \leq f_{11} \leq 0.0436$$

where, **A** is the constraint matrix and **b** is the constraint vector (Appendix 1).

The accuracy of the quadratic programming method was assessed by calculating the percent difference between the observed age-specific time-series from 1978-2004 and the time-series predicted from the black sea bass population Leslie matrix, whose parameters were estimated above, and the 1978 age-specific abundance from SEDAR (2005).

(ii) Estimating Fishing Mortality and Catch

Age-specific fishing mortality was a function of age-specific survival and natural mortality, such that

(7) $$F_i = -\ln(s_i) - M$$

where, F_i is age-specific fishing mortality; s_i is age-specific survival (estimated above); and M is natural mortality. M was constant across all age-classes (M=0.30; SEDAR 2005).

The model evaluated the extent of reef necessary to stabilize the black sea bass population growth rate (i.e. $\lambda=1$) with constant, age-specific catch across all model years. Catch was calculated based on 2004 age-specific abundance (N_i), because this was the last year for which reliable abundance data were available (SEDAR 2005). Catch was estimated as:

$$C_i = (F_i)(N_i)(1-e^{-(F_i+M)})(1/(F_i+M)) \quad (8)$$

where, C_i denotes age-specific catch and N_i denotes age-specific abundance. The parameters F_i and M were described above.

(iii) Estimating Survival in the Presence of Oyster Reef

Restored oyster reef increases the abundance of age-0 black sea bass by $3.9\text{x}10^4$ fish per km^2 oyster reef per year (Peterson et al. 2003). The following equation was used to estimate total abundance of age-0 black sea bass in the presence of restored oyster reef:

$$N_0' = N_0 + ((\mathit{reef})(3.9\text{x}10^4)) \quad (9)$$

where, N_0' is age-0 abundance in the presence of restored reef; N_0 is the 2004 black sea bass age-0 abundance (SEDAR 2005); and *reef* is the area (km^2) of restored oyster reef. To calculate the abundance of age-1 black sea bass in the presence of restored oyster reef, age-0 abundance in the presence of the reef was multiplied by age-0 survival. The abundance of older age-classes was calculated from age-0 abundance in the presence of the reef and s_i, estimated above (Table 2).

Age-specific fishing mortality in the presence of restored oyster reef was estimated by minimizing the difference between catch calculated with 2004 abundance (SEDAR 2005) and catch calculated with reef-enhanced abundance via the equation:

$$\underset{\mathbf{f'}}{\text{Minimize}} \left\| \mathbf{c} - ((\mathbf{n'})\cdot(\mathbf{f'})\cdot(1-e^{-(\mathbf{f'}+\mathbf{m})})\cdot(1/(\mathbf{f'}+\mathbf{m})) \right\|^{2} \qquad (10)$$

where, **c** is the vector (12x1) of 2004 age-specific catch in the presence of restored oyster reef; **n’** is the vector (12x1) of age-specific abundance in the presence of the oyster reef; **f’** is the vector (12x1) of age-specific fishing mortality in the presence of the oyster reef; and **m** is the vector (12x1) of constant natural mortality.

Age-specific black sea bass survival in the presence of the restored oyster reef was calculated from fishing and natural mortality as:

$$s_i' = e^{-(F_i' + M)} \qquad (11)$$

where, s_i' is age-specific survival in the presence of restored oyster reef and F_i' is age-specific fishing mortality in the presence of restored oyster reef. The parameter M was described above.

(iv) Estimating Necessary Restored Reef Area

A binary search was used to determine the area of restored reef necessary to stabilize the black sea bass population growth rate. Oyster reef area was constrained between $1\text{x}10^{-6}$ km^2 and an arbitrary ceiling ($1\text{x}10^{3}$ km^2), and the black sea bass population Leslie matrix was constructed from s_i' (calculated above) and f_i. In the first step of the binary function, λ of the black sea bass population Leslie matrix was calculated with the median reef area (500 km^2;

guess 1). If $\lambda<1$, λ of the black sea bass population Leslie matrix was calculated with the median reef area between guess one (500 km^2) and the $1x10^3$ km^2. If $\lambda>1$, λ of the Leslie matrix was recalculated with the median reef area between $1x10^{-6}$ km^2 and guess 1 (500 km^2). This process was continued until the reef area yielding $\lambda=1$ was reached.

2. Evaluating Management Strategies

(i) Oyster Reef Restoration

a) Black Sea Bass Catch in Response to Oyster Restoration

Catch of black sea bass was a function of survival, fishing mortality, natural mortality, and abundance. Black sea bass abundance during the 30 year model period was calculated from the Leslie Matrix as:

$$\mathbf{n'}_{(t+1)} = \mathbf{L'n}_{(t)} \qquad (12)$$

where, $\mathbf{n'}_{(t+1)}$ is the vector (12x1) of age-specific abundance at model year t+1 in the presence of restored oyster reef; **L'** is the population Leslie matrix (12x12) in the presence of restored oyster reef; and $\mathbf{n'}_{(t)}$ is the vector (12x1) of age-specific abundance at model year t in the presence of restored oyster reef. Model year 1 abundance was the 2004 age-specific abundance, because this is the last year for which reliable data were available (SEDAR 2005).

There are 12 black sea bass age-classes (age-0 through age-11). During the fist model year, the first age-0 black sea bass cohort recruits to the oyster reef. At this time, only age-0 survival is affected by the reef. Therefore, age-0 survival can be represented as s_0' and age-1 through age-11 survival can be represented as s_i. During the second year of the model, a new cohort of age-0 individuals recruits to the reef, and the surviving age-0 individuals from the previous year move to age-1. At this time, age-0 and age-1 survival is affected by the reef, and can be represented as s_i'. Age-2 through age-11 survival remains unaffected by the oyster reef, and can be represented as s_i. During each of the next 10 model years, a new cohort of age-0 black sea bass recruits to the reef each year, surviving individuals move to the next age-class, and the survival of an additional age-class is affected by the reef and can be represented as s_i'. During the 12th model year, individuals in every age-class experience age-0 in the presence of the oyster reef, and the survival of all age-classes is affected by the reef. Thus, during the first 12 model years, a new black sea bass population Leslie matrix is constructed for each year from the appropriate age-specific survival (s_i or s_i') and f_i (Table 3).

Assuming the proportion of total harvest caught by the commercial and recreational fishery does not change through time, commercial and recreational catch during each model year was modeled as:

$$C\mathit{bsbcomm}'_t = \mathit{cbsb}\sum_{i=0}^{11}(N'_i)(F'_i)(1-e^{-(F'_i+M)})(1/(F'_i+M) \tag{13}$$

$$C\mathit{bsbrec}'_t = (1-\mathit{cbsb})\sum_{i=0}^{11}(N'_i)(F'_i)(1-e^{-(F'_i+M)})(1/(F'_i+M) \tag{14}$$

respectively. $Cbsbcomm'_t$ is annual black sea bass commercial catch in the presence of restored oyster reef, summed across all age-classes; $Cbsbrec'_t$ is annual black sea bass recreational catch in the presence of restored oyster reef, summed across all age-classes; *cbsb* is the proportion of black sea bass catch harvested by the commercial fishery (*cbsb* = 0.542; SEDAR 2005; NMFS 2004); N'_i is age-specific black sea bass abundance in the presence of restored oyster reef; s'_i is age-specific black sea bass survival in the presence of restored oyster reef; and F'_i is age-specific black sea bass fishing mortality in the presence of restored oyster reef. The parameter M was described above.

b) Oyster Reef Restoration: Value Derived from Black Sea Bass Catch

Two economic benefit schedules were examined for oyster reef restoration. In the first schedule, we assumed that oyster reef restoration was completed in a single year, previous to the start of the model, and benefits began accruing during model year 1. In the second benefit schedule, the economic benefits of oyster reef restoration were delayed five years, allowing realistic time for reef completion. Assuming the value of black sea bass remains constant over the 30 year model period (a conservative assumption), and assuming that the dock-side price accurately reflects the economic value of the black sea bass commercial fishery, the net present value (NPV) of oyster reef restoration derived from commercial black sea bass catch was calculated as:

(15) $$NPVbsbcomm' = (wbsb)(pbsb)\sum_{t=1}^{30}(Cbsbcomm'_t)(1/(1+r)^t$$

(16) $$NPVbsbcommd' = (wbsb)(pbsb)\ (\sum_{t=1}^{5}(Cbsbcomm'''_t)(1/(1+r)^t)\sum_{t=6}^{30}(Cbsbcomm'_t)(1/(1+r)^t)$$

where, NPV*bsbcomm*'is NPV of black sea bass commercial catch under the immediate benefits schedule, summed across all model years; t is the model year; w*bsb* is the average weight per harvested fish (kg per fish); p*bsb* is the average dockside price per fish (USD per fish); r is the discount rate (r=0.03 and r=0.07, EPA 2005); NPV*bsbscomm*d' is the NPV of black sea bass commercial catch under the delayed benefits schedule, summed across all model years; and $Cbsbcomm'''_t$ is the black sea bass commercial catch if no management action is taken (see below for calculation). The parameter $Cbsbcomm'_t$ was described above. The value of future catch is discounted in recognition of most people's preference to consume now rather than later (Boardman et al. 2005).

The average weight per harvested black sea bass (w*bsb*) was calculated as:

(17) $$wbsb = (lbsb_{2004})/(Cbsbcomm_{2004})$$

where, $lbsb_{2004}$ is total the commercial black sea bass landings (kg) in North Carolina, South Carolina, Georgia, and Florida in 2004 and $Cbsbcomm_{2004}$ is back sea bass catch during 2004 (NMFS 2004, w*bsb* = 0.23kg/fish).

The average price per black sea bass (p*bsb*) was calculated as

(18) $$pbsb = (vbsb_{2004})/(lbsb_{2004})$$

where, $\mathrm{v}bsb_{2004}$ is the total dockside value (USD) of commercial black sea bass landings in 2004, and the parameter $\mathrm{l}bsb_{2004}$ was described above ($\mathrm{p}bsb$ = \$3.60/kg, NMFS 2004).

Black sea bass support an economically important recreational catch-and-release recreational fishery, and the economic value of black sea bass recreational fishing is a function of both recreational catch-and-consume and recreational catch-and-release fishing. These values depend on angler willingness to pay (WTP) per fish per day (\$5.30 USD for black sea bass and other species; EPA 2004), which represents the economic value of the recreational fishing experience, and the commercial value per fish (($\mathrm{w}bsb$)($\mathrm{p}bsb$)), which represents the recreational anglers' avoided cost of buying black sea bass on the commercial market. The net present value (NPV) of oyster reef restoration derived from recreational black sea bass catch was calculated as:

(19) $$\mathrm{NPV}bsbrec\mathrm{con}' = (5.30+((\mathrm{p}bsb)(\mathrm{w}bsb))\sum_{t=1}^{30}(\mathrm{C}bsbrec'_{t})(1/(1+r)^{t}$$

(20) $$\mathrm{NPV}bsbrec\mathrm{dcon}' = (5.30+((\mathrm{p}bsb)(\mathrm{w}bsb))(\sum_{t=1}^{5}(\mathrm{C}bsbrec'''_{t})(1/(1+r)^{t})\sum_{t=6}^{30}(\mathrm{C}bsbrec'_{t})(1/(1+r)^{t})$$

(21) $$\mathrm{NPV}bsbrec\mathrm{rel}' = (\mathrm{ratio}bsb)(5.30)\sum_{t=1}^{30}(\mathrm{C}bsbrec'_{t})(1/(1+r)^{t}$$

(22) $$\mathrm{NPV}bsbrec\mathrm{drel}' = (\mathrm{ratio}bsb)(5.30)\ (\sum_{t=1}^{5}(\mathrm{C}bsbrec'''_{t})(1/(1+r)^{t})\sum_{t=6}^{30}(\mathrm{C}bsbrec'_{t})(1/(1+r)^{t})$$

(23) $$\mathrm{NPV}bsbrec' = \mathrm{NPV}bsbrec\mathrm{con}' + \mathrm{NPV}bsbrec\mathrm{rel}'$$

(24) $$\mathrm{NPV}bsbrec\mathrm{d}' = \mathrm{NPV}bsbrec\mathrm{dcon}' + \mathrm{NPV}bsbrec\mathrm{drel}'$$

where, NPV*bsbrec*con’ is the NPV of oyster reef restoration derived from the black sea bass recreational catch-and-consume fishery under the immediate benefits schedule; $5.30 is WTP per fish per day for black sea bass and other species; NPV*bsbrec*dcon’ is the NPV of oyster reef restoration derived from black sea bass recreational catch-and-consume fishing under the delayed benefit schedule; $C\mathit{bsbrec}'''_t$ is the annual recreational catch of black sea bass if management action is not taken (calculated below); NPV*bsbrec*rel’ is the NPV of oyster reef restoration derived from the black sea bass recreational catch-and-release fishery under the immediate benefit schedule; ratio*bsb* is the ratio of the number of black sea bass harvested by the recreational catch-and-consume fishery compared to the number of fish caught and released by the recreational fishery (ratio*bsb* = 3.78; NMFS 2006); NPV*bsbrec*drel’ is the NPV of oyster reef restoration derived from black sea bass recreational catch-and-release fishing under the delayed benefit schedule; NPV*bsbrec*’ is the total NPV of oyster reef restoration derived from black sea bass recreational fishing under the immediate benefit schedule; and NPV*bsbrec*d’ is the total NPV of oyster reef restoration derived from black sea bass recreational fishing under the delayed benefit schedule. All other parameters were described above.

c) Catch of other Species in Response to Oyster Restoration

Oyster reef restoration enhances the abundance of other commercially and recreationally valuable species, including gag grouper, gray snapper, sheepshead, and stone crab (Peterson et al. 2003). The extent of restored oyster reef necessary to stabilize the black sea bass population growth rate simultaneously increased the annual age-0 abundance of gag grouper, gray snapper, sheepshead, and stone crab as follows:

(25) $$Nsp'_0 = (reef)(Esp)$$

where, Nsp'_0 is the species-specific increase in age-0 individuals, *reef* is the reef area (km^2) estimated above and E*sp* is the species-specific age-0 abundance enhancement per km^2 (Table 4; Peterson et al. 2003).

The annual species-specific increase in recruitment to the commercial and recreational fisheries for species other than black sea bass was estimated as:

(26) $$Fishsp' = (Nsp'_0)(e^{Msp})^{asp}$$

where, Fish*sp*' is the annual, species-specific recruitment increase as a result of oyster reef restoration; M*sp* is the species-specific natural mortality rate; and *asp* is the species-specific recruitment age (Table 4). The parameter Nsp'_0 was calculated above.

d) Oyster Reef Restoration: Value Derived from Gag Grouper, Gray Snapper, Sheepshead and Stone Crab

Assuming a constant proportion of commercial and recreational harvest through time, the species-specific oyster reef derived commercial and recreational catch of species other than black sea bass, which was calculated as:

(27) $$Cspcomm'_t = (ratesp)(csp)(Fishsp')$$

(28) $$Csprec'_t = (ratesp)(1-csp)(Fishsp')$$

where, $Cspcomm'_t$ and $Csprec'_t$ represent the commercial and recreational catch of each species added as a function of oyster reef restoration, respectively; rate*sp* is the species-specific annual exploitation rate (proportion of total population harvested annually; Table 4); and *csp* is the proportion total catch harvested by the commercial fishery for each species (Table 4). The parameter Fish*sp*' was discussed above.

Assuming the value of each species other than black sea bass remains constant through time, and that the dock-side price accurately reflects the value of each fishery, the NPV of the additional commercial catch was estimated as:

$$\text{(29)} \qquad \mathrm{NPV}\mathit{spcomm}' = (\mathrm{w}\mathit{sp})(\mathrm{p}\mathit{sp})\sum_{t=\mathit{asp}}^{30}(\mathrm{C}\mathit{spcomm}'_{t})(1/(1+\mathrm{r})^{t})$$

$$\text{(30)} \qquad \mathrm{NVP}\mathit{pcomm}\mathrm{d}' = (\mathrm{w}\mathit{sp})(\mathrm{p}\mathit{sp})\sum_{t=(\mathit{asp}+6)}^{30}(\mathrm{C}\mathit{spcomm}'_{t})(1/(1+\mathrm{r})^{t})$$

where, NPV*spcomm*' is the species-specific NPV of the commercial catch added as a function of oyster reef restoration under the immediate benefit schedule; w*sp* is the average, species-specific weight per harvested individual (kg); p*sp* is the average, species-specific price per individual (USD); and NPV*spcomm*d' is the species-specific NPV of the commercial catch added as a function of oyster reef restoration under the delayed benefit schedule (USD). The parameters $\mathrm{C}\mathit{spcomm}'_{t}$, *asp*, r, and t were described above.

For all species, p*sp* was calculated from the 2004 revenue and the total landings (kg) as:

$$\text{(31)} \qquad \mathrm{p}\mathit{sp} = (\mathrm{v}\mathit{sp}_{2004})/(\mathrm{l}\mathit{sp}_{2004})$$

where, $\mathrm{v}sp_{2004}$ is the average, species-specific dockside value in NC, SC, GA, and FL in 2004 (USD) and $\mathrm{l}sp_{2004}$ is the total, species-specific commercial landings, by weight, in NC, SC, GA, and FL in 2004 (kg).

The parameter $\mathrm{w}sp$ was estimated differently for gag grouper, gray snapper, sheepshead, and stone crab. Gag grouper $\mathrm{w}sp$ ($\mathrm{w}gag$) was available directly from the literature (5.95kg per fish; SEDAR 2006**)**. Gray snapper $\mathrm{w}sp$ ($\mathrm{w}gs$) was calculated as (Burton 2001):

(32) $$\mathrm{w}gs = (7.22 \times 10^{-9})(\mathrm{TL}gs^{3.11})$$

where, $\mathrm{TL}gs$ is the average harvest length (mm TL) from 1986-1997 (500mm, Burton 2001). Sheepshead $\mathrm{w}sp$ ($\mathrm{w}sh$) was calculated as (Murphy and MacDonald 2000):

(33) $$\mathrm{w}sh = (2.24\mathrm{x}10^{-8})(\mathrm{FL}sh_{2004})^{3.024}$$

where, $\mathrm{FL}sh_{2004}$ is the average fork length of commercially harvested fish in 2004 (324.36 mm FL, Muller et al. 2006). Stone crab landings are reported in kilograms of claws. Thus, the stone crab $\mathrm{w}sp$ ($\mathrm{w}stc$) was calculated as:

(34) $$\mathrm{w}stc = (\mathrm{l}stc_{2004})(\mathrm{CLAW}stc_{2004})(\mathrm{CLAWper}stc)$$

where, $\mathrm{l}stc_{2004}$ is the 2004 Florida stone crab landings in weight (Kg claws; Muller et al. 2006); $\mathrm{CLAW}stc_{2004}$ is the 2004 Florida stone crab landings in number (number of claws; Muller et al. 2006); and $\mathrm{CLAWper}stc$ is the average number of claws landed per stone crab (Muller et al. 2006). These calculations were based on Florida landings because Florida is the only state in which landings are recorded in number of claws and in weight of claws.

Florida is also the only state which tracks claws per crab landed. See Table 4 for species-specific data and sources.

The NPV of gag grouper, gray snapper, and sheepshead recreational catch-and-consume fishing derived from oyster reef restoration was estimated as

$$(35)\qquad \mathrm{NPV}\mathit{sprec}\mathrm{con}' = (5.30+(\mathrm{w}\mathit{sp})(\mathrm{p}\mathit{sp}))\sum_{t=asp}^{30}(\mathrm{C}\mathit{sprec}'_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}})$$

$$(36)\qquad \mathrm{NPV}\mathit{sprec}\mathrm{dcon}' = (5.30+(\mathrm{w}\mathit{sp})(\mathrm{p}\mathit{sp}))\sum_{t=(asp+6)}^{30}(\mathrm{C}\mathit{sprec}'_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}})$$

where NPV*sprec*con' is the species-specific NPV of recreational catch-and-consume fishing added as a function of the reef under the immediate benefit schedule; US $5.30 is the WTP per fish per day; and NPV*sprec*cond' is the species-specific NPV of the recreational catch-and-consume fishing added as a function of the reef under the delayed benefit schedule. The parameters $\mathrm{C}\mathit{sprec}'_{\mathrm{t}}$, t, *asp*, and r were described above. The WTP per fish per day represents the value of the recreational fishing experience, while (w*sp*)(p*sp*) represents the avoided cost of buying the fish on the commercial market.

Sheepshead and gray snapper support economically important recreational catch-and-release fisheries. The NPV of oyster reef restoration derived from recreational catch-and-release fishing of species other than black sea bass was calculated as:

$$(37)\qquad \mathrm{NPV}\mathit{sprec}\mathrm{rel}' = (\mathrm{ratio}\mathit{sp})(5.30)\sum_{t=asp}^{30}(\mathrm{C}\mathit{sprec}'_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}})$$

(38) $$\mathrm{NPV}\mathit{sprec}\mathrm{drel}' = (\mathrm{ratio}\mathit{sp})(5.30)\sum_{t=(\mathit{asp}+6)}^{30}(\mathrm{C}\mathit{sprec}'_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}})$$

where, NPV*sprec*rel' is the species-specific net present value of recreational catch-and-release landings added as a function of restored oyster reef under the immediate benefit schedule; ratio*sp* is the ratio of the number of fish harvested by the recreational catch-and-consume fishery compared to the number of fish caught and released in the recreational fishery (Table 4; NMFS 2006); US $5.30 is the WTP per fish per day for gag grouper, gray snapper, sheepshead, stone crab, and other species (EPA 2004); and NPV*sprec*drel' is the species-specific NPV of recreational catch-and release fishing added as a function of restored oyster reef under the delayed benefit schedule. Information on the economic benefit of gag grouper and stone crab recreational catch-and-release fishing was not available, and the NPV*sprec*rel' and NPV*sprec*drel' was assumed to be 0 for gag grouper and stone crab. The parameters $\mathrm{C}\mathit{sprec}'_{\mathrm{t}}$, r, and t were discussed above.

The total species-specific NPV of oyster reef restoration derived from additional recreational fishing of gag grouper, gray snapper, sheepshead, and stone crab was calculated from the equations:

(39) $$\mathrm{NPV}\mathit{sprec}' = \mathrm{NPV}\mathit{sprec}\mathrm{con}' + \mathrm{NPV}\mathit{sprec}\mathrm{rel}'$$

(40) $$\mathrm{NPV}\mathit{sprec}\mathrm{d}' = \mathrm{NPV}\mathit{sprec}\mathrm{dcon}' + \mathrm{NPV}\mathit{sprec}\mathrm{drel}'$$

where, NPV*sprec*' is the species-specific NPV of recreational fishing added as a function of oyster reef restoration for species other than black sea bass under the immediate benefit schedule and NPV*sprec*d' is the species-specific NPV of recreational fishing added as a function of oyster reef restoration for species other than black sea bass under the delayed benefit schedule. The parameters NPV*sprec*con', NPV*sprec*rel', NPV*sprec*dcon', and NPV*sprec*drel' were defined above.

e) Costs of Oyster Reef Restoration

The economic costs of oyster reef restoration were estimated per km^2 based on North Carolina's 2004 sub-tidal oyster reef restoration methods (\$10,327,594/km^2, 2004 USD; S. Slade, NCDMF, personal communication). Cost estimates were based on 2004 values because benefit estimates are based on 2004 data. These estimates include the price of the limestone rip-rap material that forms the reef foundation, vessel fuel, labor, vessel supplies, and boat support operations. When calculating the cost of oyster reef restoration, we assume the reefs are no-take with respect to oyster harvesting, and there is no maintenance cost.

The cost of oyster reef restoration accrued on two schedules, depending on the benefit schedule. If the benefits of oyster reef restoration began during model year one, then we assumed oyster reef restoration was completed in one year, previous to the start of the model, and the total, one-time cost of oyster reef restoration was calculated by multiplying the cost per km^2 by the total reef area via the equation:

$$cost = (reef)(\$10{,}327{,}594/\text{km}^2) \tag{41}$$

where, *cost* is the total cost of restoring oyster reef under the immediate benefit schedule, \$10,327,594 is the cost per km^2 reef and *reef* was discussed above. If the benefits of oyster reef restoration were delayed five years, then the cost of oyster reef restoration was distributed proportionally over the first five model years, and was calculated using the equation:

$$(42) \qquad cost\text{d} = (\$10{,}327{,}594/\text{km}^2)\sum_{t=1}^{5}(reef)(1/5)(1/(1+r)^t)$$

where, *cost*d is the cost of restoring oyster reef under the delayed benefit schedule and the parameters t, *reef*, and r were discussed above.

The net economic value of oyster reef restoration was estimated as:

$$(43) \qquad \text{NPV}total\text{'} = (\text{NPV}bsbcomm\text{'} + \text{NPV}bsbrec\text{'} + \sum\text{NPV}spcomm\text{'} + \sum\text{NPV}sprec\text{'}) - cost$$

$$(44) \qquad \text{NPV}total\text{d'} = (\text{NPV}bsbcomm\text{d'} + \text{NPV}bsbrec\text{d'} + \sum\text{NPV}spcomm\text{d'} + \sum\text{NPV}sprec\text{d'}) - cost\text{d}$$

where, NPV*total*' is the total net present economic value of oyster reef restoration under the immediate benefit schedule; ∑NPV*spcomm*' is the sum of the NPV of oyster reef restoration derived from commercial fishing of species other than black sea bass under the immediate benefit schedule; ∑NPV*sprec*' is the sum of the NPV of oyster reef restoration derived from recreational fishing of species other than black sea bass under the immediate benefit schedule; NPV*total*d' is the total net present economic value of oyster reef restoration under the delayed benefit schedule; ∑NPV*spcomm*d' is the sum of the NPV of oyster reef restoration derived from commercial fishing of species other than black sea bass under the delayed benefit schedule; and ∑NPV*sprec*d' is the sum of the NPV of oyster reef restoration derived from recreational fishing of species other than black sea bass under the delayed benefit schedule. The variables NPV*bsbcomm*', NPV*bsbrec*', and *cost*d were described above.

(ii) Reduced Fishing Mortality

a) Black Sea Bass Catch in Response to Reduced Fishing Mortality

The declining black sea bass population growth rate in the US South Atlantic is driven, in part, by high fishing mortality. A binary search was used to estimate the fishing mortality (F) reduction necessary to stabilize the black sea bass population growth rate. The reduced F was calculated as:

$$F''_i = F_i - (F_i)(Red) \tag{45}$$

where, F''*i* is the reduced, age-specific black sea bass F and *Red* is the percent reduction. The parameter F_i was described above.

Survival of black sea bass under a reduced F scenario was estimated as:

$$s''_i = e^{-(F''i + M)} \tag{46}$$

where, s''_i is age-specific survival under the reduced F scenario. The parameters F''_i and M were described above.

In the first function step, black sea bass survival was estimated with a 50% reduction in F ($Red = 0.50$). The parameter f_i was described above, and did not change in response to decreased F. Survival with reduced F and fertility were used to construct a black sea bass population Leslie matrix, whose λ was calculated. If $\lambda<1$, black sea bass survival was recalculated with a 25% reduction in F ($Red = 0.25$), and if $\lambda>1$, survival was calculated with a 75% reduction in F ($Red = 0.75$). Fertility and the new survival were used to construct a new black sea bass population Leslie matrix, and the λ of this Leslie matrix was calculated. This process was repeated until a percent reduction in F yielding λ=1 was reached.

Two F reduction schedules were examined. In the first schedule, the black sea bass Leslie population matrix reflected the full reduction during the first model year, and survival during all model years was equal to s''_i. In the second schedule, F was reduced proportionally over the first 12 model years (e.g. reduction during the first model year was 1/12 the total reduction, and reduction during the twelfth equaled the full reduction). Therefore, during the first 12 model years, s''_i increased as F''_i decreased, (the parameter f_i remains constant throughout the model), and a new population Leslie matrix was constructed for each of the first 12 years from fertility and the proportionally increasing survival. During model years 13-30, the Leslie matrix was constant. This proportional reduction reflected the 12 year lag between reef restoration and the full realization of reef benefits, and accounted for possible political challenges associated with implementing a large F decrease in one year.

For both F reduction schedules, annual abundance of black sea bass under the reduced F scenario was projected from the Leslie population matrix as:

$$\mathbf{n''}_{(t+1)} = (\mathbf{L''})(\mathbf{n''}_{(t)}) \tag{47}$$

where, $\mathbf{n''}_{(t+1)}$ is the vector (12x1) of age-specific abundance during model year t+1; $\mathbf{L''}$ is the black sea bass Leslie population matrix (12x12); and $\mathbf{n''}_{(t)}$ is the vector (12x1) of age-specific abundance during model year t. Abundance during model year 1 was the 2004 age-specific abundance (SEDAR 2005).

Commercial and recreational catch during each model year was estimated as:

(48) $$\mathrm{C}\mathit{bsbcomm}''_{\mathrm{t}} = \mathit{cbsb}\sum_{i=0}^{11}(\mathrm{N}''_{i})(\mathrm{F}''_{i})(1-e^{-(\mathrm{F}''_{i}+\mathrm{M})})(1/(\mathrm{F}''_{i} + \mathrm{M}))$$

(49) $$\mathrm{C}\mathit{sbsrec}''_{\mathrm{t}} = (1-\mathit{cbsb})\sum_{i=0}^{11}(\mathrm{N}''_{i})(\mathrm{F}''_{i})(1-e^{-(\mathrm{F}''_{i}+\mathrm{M})})(1/(\mathrm{F}''_{i} + \mathrm{M}))$$

respectively. C*bsbcomm*$''_{\mathrm{t}}$ is commercial catch during each model years and C*bsbrec*$'''_{\mathrm{t}}$ is recreational catch during each model year under the reduced F schedule for both benefit schedules. The parameters *i*, *cbsb,* s$''_{i}$, F$''_{i}$, and M were described above.

b) Reduced Fishing Mortality: Value Derived from Black Sea Bass Catch

The economic value derived from the commercial and recreational black sea bass catch under this scenario was estimated as:

(50) $$\mathrm{NPV}\mathit{bsbcomm}'' = (\mathrm{w}\mathit{bsb})(\mathrm{p}\mathit{bsb})\sum_{\mathrm{t}=1}^{30}(\mathrm{C}\mathit{bsbcomm}''_{\mathrm{t}})(1/(\mathrm{r}+1)^{\mathrm{t}}))$$

(51) $$\mathrm{NPV}\mathit{bsbrec}\mathrm{con}'' = (5.30+(\mathrm{w}\mathit{bsb})(\mathrm{p}\mathit{bsb}))\sum_{\mathrm{t}=1}^{30}(\mathrm{C}\mathit{bsbrec}''_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}}))$$

(52) $$\mathrm{NPV}\mathit{bsbrec}\mathrm{rel}'' = (\mathrm{ratio}\mathit{bsb})(5.30)\sum_{\mathrm{t}=1}^{30}(\mathrm{C}\mathit{bsbrec}''_{\mathrm{t}})(1/(1+\mathrm{r})^{\mathrm{t}})$$

(53) $$\mathrm{NPV}\mathit{bsbrec}'' = \mathrm{NPV}\mathit{bsbrec}\mathrm{con}'' + \mathrm{NPV}\mathit{bsbrec}\mathrm{rel}''$$

where, NPV*bsbrec*con'' is the NPV of black sea bass commercial fishing under the reduced F scenario for both benefit schedules; NPV*bsbrec*con'' is the NPV of black sea bass recreational catch-and-consume fishing; NPV*bsbrec*rel'' is the NPV of black sea bass recreational catch-and-release fishing; and NPV*bsbrec*'' is the total NPV of black sea bass recreational fishing under the reduced F scenario for both benefit schedules. The parameters w*bsb*, p*bsb*, C*bsbrec*’’$_{t}$, r, ratio*bsb*, and C*bsbrec*’’$_{t}$ were described above.

Assuming the scenario of reduced F does not increase significantly the need for new management personnel, there is no cost associated with reduced F. The net economic value derived from reduced F was estimated as:

$$\text{NPV}\textit{total}'' = \text{NPV}\textit{bsbcomm}'' + \text{NPV}\textit{bsbrec}'' \tag{54}$$

where, NPV*total*’’ is the net economic value of the reduced F scenario for both benefit schedules. The parameters NPV*bsbcomm*’’ and NPV*bsbrec*’’ were described above.

(iii) Management Inaction

a) Black Sea Bass Catch in Response to Management Inaction

If current black sea bass management does not change, the black sea bass population abundance will continue to decline. Annual age-specific abundance under an inaction scenario was estimated as:

$$\mathbf{n'''}_{\mathbf{(t+1)}} = (\mathbf{L'''})(\mathbf{n'''}_{\mathbf{(t)}}) \tag{55}$$

where, $\mathbf{n'''}_{\mathbf{(t+1)}}$ is the vector (12x1) of age-specific abundance at time t+1; $\mathbf{L'''}$ is the black sea bass population Leslie population matrix (12x12); and $\mathbf{n'''}_{\mathbf{(t)}}$ is the vector (12x1) of age-specific abundance at time t under the management inaction scenario.

Commercial and recreational catch under this scenario were estimated as:

$$\text{C}\textit{bsbcomm}'''_{\text{t}} = \textit{cbsb}\sum_{t=1}^{11}(\text{N}'''_{i})(\text{F}'''_{i})(1-e^{-(\text{F}'''_{i}+\text{M})})/(1/(\text{F}'''_{i} + \text{M}) \tag{56}$$

(57)
$$C\mathit{bsbrec}'''_t = (1-\mathit{cbsb})\sum_{t=1}^{11}(N'''_i)(F'''_i)(1-e^{-(F'''_i+M)})/(1/(F'''_i + M)$$

where, $C\mathit{bsbcomm}'''_t$ is annual black sea bass commercial catch; $C\mathit{bsbrec}'''_t$ is annual black sea bass recreational catch; N'''_i is age-specific abundance; and F'''_i is age-specific F (equal to F_i and constant across all model years) under the management inaction scenario. The parameters *cbsb* and M were described above.

b) Management Inaction: Value derived from Black Sea Bass Catch

The NPV of the commercial and recreational catch under the management inaction scenario was estimated as:

(58)
$$NPV\mathit{bsbcomm}''' = (w\mathit{bsb})(p\mathit{bsb})\sum_{t=1}^{30}(C\mathit{bsbcomm}'''_t)(1/(1+r)^t$$

(59)
$$NPV\mathit{bsbrec}\mathrm{con}''' = (5.30+((w\mathit{bsb})(p\mathit{bsb}))\sum_{t=1}^{30}(C\mathit{bsbrec}'''_t)(1/1+r)^t$$

(60)
$$NPV\mathit{bsbrec}\mathrm{rel}''' = (\mathrm{ratio}\mathit{bsb})(5.30)\sum_{t=1}^{30}(C\mathit{bsbrec}'''_t)(1/(1+r)^t$$

(61)
$$NPV\mathit{bsbrec}''' = NPV\mathit{bsbrec}\mathrm{con}''' + NPV\mathit{bsbrec}\mathrm{rel}'''$$

respectively. NPV*bsbcomm*''' is the NPV of black sea bass commercial fishing; NPV*bsbrec*con''' is the NPV of black sea bass recreational catch-and-consume fishing; NPV*bsbrec*rel''' is the NPV of black sea bass recreational catch-and-release fishing; and NPV*bsbrec*''' is the total NPV of black sea bass recreational fishing under the management inaction scenario. All other parameters were described above.

The net economic value derived from management inaction was estimated as:

(62) $$\text{NPV}\mathit{total}''' = \text{NPV}\mathit{bsbcomm}''' + \text{NPV}\mathit{bsbrec}''$$

where, NPV*total*''' is the total net economic value of the management inaction scenario. NPV*bsbcomm*''' and NPV*bsbrec*''' were described above.

(iv) Comparing Management Strategies

The net economic value of each management scenario (reef restoration, reduced F, and management inaction) was compared, and the scenario with the highest net value was identified as the most economically effective management alternative.

3. Sensitivity Analysis

The cost-effectiveness of reef restoration compared to reduced F or management inaction was primarily driven by the area of reef that must be restored (see below). Given the non-linear, non-monotonic behavior of our computer simulation model (see Discussion), we assessed the sensitivity of the reef area necessary to stabilize the black sea bass population growth rate via a Random Sampling-High Dimensional Model Representation (RS-HDMR) approach (Ziehn and Tomlin 2009). RS-HDMR maps the input-output relationships of a given model, producing a meta-model which provides first and second order variance-based sensitivity indices (s_i and s_{ij} respectively). First order sensitivity indices measure the fractional contribution of each parameter to the output variance, and second order indices measure the interactive effects of parameter pairs on model output. First and second order sensitivity indices allow one to rank the relative importance of each parameter and parameter interaction (Li et al. 2002; Ziehn and Tomlin 2009).

RS-HDMR sensitivity analysis was conducted using the MATLAB Graphical User Interface-High Dimensional Model Representation (GUI-HDMR) software package (Ziehn and Tomlin 2009). The user supplies two sets of input-output samples, derived from Monte Carlo model evaluations. With the first set, GUI-HDMR creates the meta-model representing the relationship between input and output variance. The second set of supplied values was used to calculate coefficients of determination (R^2) of the meta-model. The R^2 is a measure of relative accuracy of the meta-model in predicting the input-output relationship of the original model. R^2 values range from zero to one, with one indicating 100% accuracy.

The RS-HDMR meta-model was derived from 1,000 input-output Monte Carlo simulations, sampled from a uniform distribution of parameter values. Model accuracy was tested against a second set of 1,000 input-output Monte Carlo simulations. Because the resulting R^2 were relatively low (see Results), a second meta-model was derived from 1,000 additional Monte Carlo simulations, and R^2 was similarly tested using a set of 1,000 simulations.

Parameter Distributions: Fertility and Survival

The quadratic programming methods used to estimate black sea bass demographic rates (described above) lack straightforward methods for calculating uncertainty in these parameters. To estimate uncertainty, a set of possible values for each age-specific demographic parameter was estimated via a quadratic programming routine from bootstrap replicate time-series of the 1978-2004 time-series of black sea bass abundance (SEDAR

2005). Time-series length ranged from five to 26 years, and every possible consecutive combination of years was sampled.

The mean percent difference between demographic rates estimated from the full time-series (27 years) and bootstrap sub-samples ranging from five to 26 years was 33%. For time-series less than five years, the mean percent difference in demographic rates estimated from the full time-series and the sub-sampled time-series was 61% (Fig. 2). Thus, five years was chosen as the shortest time-series for the bootstrap estimation of demographic rates. These calculations excluded parameters whose percent difference between sub-sample time-series parameter values and full time-series parameter values was greater than 100 for more than half the sub-sampled time-series.

The RS-HDMR GUI software requires uniform parameter distributions. Thus, the maximum and minimum of each set of parameter values resulting from the bootstrap analysis were used to construct a uniform distribution of each parameter from which values for each Monte Carlo simulation were randomly sampled. To eliminate the correlation between survival and fertility, each age-specific parameter was sampled independently of the other parameter values.

Parameter Uncertainty: Natural Mortality

Natural mortality values were selected from a uniform distribution with a minimum value of 0.2 and a maximum value of 0.4 (SEDAR 2002).

Parameter Uncertainty: Abundance

Black sea bass stock assessments do not provide abundance error rates or estimate ranges (SEDAR 2002, 2005). To obtain the maximum possible age-specific abundance, 10,000 samples were randomly drawn from normal distributions of each age-specific abundance parameter, with mean equal to the parameter value and standard deviation equal to 50% of the parameter value (J. Hightower, NC State University, personal communication). Monte Carlo simulation parameters were randomly drawn from a uniform distribution, with maximum value equal to the maximum possible age-specific abundance and minimum value equal to zero.

Parameter Uncertainty: Abundance Enhancement of Black Sea Bass

Ranges in the enhancement of black sea bass abundance with reef restoration were not available from the literature (Peterson et al. 2003). Therefore, values of abundance enhancement of black sea bass for Monte Carlo simulations were sampled from a uniform distribution with minimum zero. The maximum value was estimated by finding the maximum of 10,000 random samples of a normal distribution with mean 0.39 fish per $10m^2$ restored oyster reef and standard deviation 0.6 fish per 10 m^2 oyster reef (Lenihan et al. 2001). This standard deviation was chosen because the means provided in Peterson et al. (2003) did not include estimates of variance, and because black sea bass densities provided in Lenihan et al. (2001), which was the only black sea bass study cited by Peterson et al. (2003), reports an on-reef age-0 density of 0.5 ± 0.6 (mean ± 1 SD) black sea bass per $10m^2$, and an off-reef density of zero.

Results:

The population Leslie matrix model predicted age-specific abundance of black sea bass with a mean proportional difference of 0.8559±.0.087 (mean±1 SD). Based on our demographic rate estimates, the black sea bass population is shrinking (λ= 0.97). The black sea bass population growth rate (λ) increased with increasing restored reef (Fig. 3), and stabilized (λ=1) when the amount of additional restored oyster reef reached a total of 52.166 km^2 along the U.S. South Atlantic Coast.

Under the immediate benefit schedule, with a discount rate of 3% (or 7%) the net present value (NPV) of restoring ~52 km^2 of oyster reef to the commercial and recreational fishery for black sea bass was $41,926,000 ($26,543,000) and $609,890,000 ($386,120,000), respectively. The NPV of oyster reef restoration derived from enhancement of other species, including gag grouper, gray snapper, sheepshead, and stone crab to commercial and recreational fishing was $21,730,000 ($13,757,000) and $32,158,000 ($20,359,000) for gag grouper commercial and recreational fishing, respectively; $72,428,000 ($4,585,400) and $131,800,000 ($83,444,000) for gray snapper commercial and recreational fishing, respectively; $543,190 ($343,890) and $38,904,000 ($24,630,000) for sheepshead commercial and recreational fishing, respectively; and $1,006,200,000 ($637,040,000) for stone crab commercial fishing. The cost of building 52.166 km^2 of oyster reef under an immediate cost and benefit schedule was $534,050,000 ($537,050,000). Thus, when the costs of building oyster reefs was subtracted from the benefit to black sea bass and other species, the overall net economic gain from oyster reef restoration under the immediate benefit schedule was \$1,356,400,000 (\$662,780,000) (Table 5). The final black sea bass population size in the presence of ~52km^2 oyster reef under the immediate benefit and cost schedule was 14,599,146 individuals (Fig 4).

Under the delayed benefit schedule, with a discount rate of 3% (or 7%) the net present value (NPV) of restoring ~52 km^2 of oyster reef to the commercial and recreational fishery for black sea bass was \$40,881,000 (\$25,628,000) and \$594,690,000 (\$372,810,000), respectively. The NPV of oyster reef restoration derived from enhancement of other species, including gag grouper, gray snapper, sheepshead, and stone crab to commercial and recreational fishing was \$16,653,000 (\$9,211,500) and \$24,644,000 (\$13,632,000) for gag grouper commercial and recreational fishing, respectively; \$5,550,500 (\$3,070,300) and \$101,010,000 (\$55,873,000) for gray snapper commercial and recreational fishing, respectively; \$416,270 (\$230,260) and \$29,814,000 (\$16,492,000) for sheepshead commercial and recreational fishing, respectively; and \$771,120,000 (\$426,550,000) for stone crab commercial fishing. The cost of building 52.166 km^2 of oyster reef under delayed cost and benefit schedule was \$489,160,000 (\$437,950,000). Thus, when the costs of building oyster reefs was subtracted from the benefit to black sea bass and other species under the delayed benefit schedule, the overall net economic gain from oyster reef restoration was \$1,095,600,000 (\$485,560,000) (Table 5). The final black sea bass population size in the presence of ~52km^2 oyster reef under a delayed benefit and cost schedule was 12,526,955 individuals.

Regardless of the benefit schedule or discount rate, F reduction was not as economically effective a management option as oyster reef restoration. For example, a 19% decrease in age-specific F stabilized the population growth rate of black sea bass (λ=1; Fig. 5). The net economic value of black sea bass commercial and recreational fishing with a 19% reduction in F under an immediate benefit schedule with a 3% (or 7%) discount rate was $35,366,000 ($22,383,000) and $514,470,000 ($325,610,000), respectively (Table 5). The final black sea bass population size under the reduced F management scenario and immediate benefit schedule was 16,141,390 individuals (Fig. 6).

The net economic value of reducing black sea bass F under a delayed benefit schedule with a 3% (or 7%) discount rate was $27,232,000 ($18,773,000) and $396,150,000 ($273,090,000), respectively (Table 5). The final black sea bass population size under the reduced F management scenario and delayed benefit schedule was 16,089,145 individuals.

The net economic gain from building oyster reefs was between 2 and 3.5 times greater than the net economic gain from management inaction. The net economic value of black sea bass commercial and recreational catch under a management inaction scenario with a 3% (or 7%) discount rate was $28,203,000 ($19,206,000) and $410,270,000 ($279,380,000), respectively (Table 5). The final population size under a management inaction scenario was 1,020,651 individuals (Fig. 7).

The RS-HDMR sensitivity analysis was performed with two separate samples of Monte Carlo simulations. Overall, the sensitivity analysis revealed that fertility and survival were the most important parameters driving the amount of restored oyster reef area necessary to stabilize the black sea bass population growth rate. Furthermore, interactions among age-specific fertility, as well as between fertility and survival, or fertility and abundance were important for determining the extent of oyster reef necessary to stabilize the black sea bass population. The RS-HDMR analysis performed with the first set of simulations had a first order coefficient of determination (R^2) equal to 0.1078 and a second order R^2 equal to 0.0437, indicating that the first order metamodel accurately predicted model output ~11% of the time and the second order metamodel accurately predicted model output ~4% of the time. Age three fertility (s_i=0.083); age one fertility (s_i=0.0459); age two fertility (s_i=0.0214); age 4 abundance (s_i=0.0084); and age two abundance (s_i=0.0078) were the most important parameters. These five parameters explained 18.59% of the meta-model variance ($\sum s_i$=0.1859). Age three and age nine fertility (s_{ij}=0.0173); age two survival and age four fertility (s_{ij}=0.0167); age one and age three fertility (s_{ij}=0.0126); age two fertility and age one abundance (s_{ij}=0.0115); and age one and age seven abundance (s_{ij}=0.0173) were the five most important pairs of parameter interactions determining the model outcome. These five interactions explained 51.10% of the meta-model variance ($\sum s_{ij}$=0.5410). The five most important first-order and five most important second-order parameters together explained 72.69% of the model variance ($\sum s_i + \sum s_{ij} = 0.7269$).

The RS-HDMR analysis performed with the second set of Monte Carlo simulations had a first order R^2 equal to 0.1188 and a second order R^2 equal to 0.0609. Age three fertility (s_i=0.0388); age two fertility (s_i=0.0194); age one fertility (s_i=0.0190); age three abundance (s_i=0.0188); and age two abundance (s_i=0.0113) were the five most important parameters.

Combined, these five parameters explained 12.14% of the total model variance ($\sum s_i$=0.1214). Age eight survival and age three fertility (s_{ij}=0.0158); age five and age six survival (s_{ij}=0.0148); age five and age seven fertility (s_{ij}=0.0115); age one survival and age seven fertility (s_{ij}=0.0105; and age three and age eight fertility (s_{ij}=0.0097) were the five most important parameter interactions. Combined, these five interactions explained 28.18% of the total model variance ($\sum s_{ij}$=0.2818). The five most important first order parameters and the five most important second order parameters explained a total of 40.31% of the total model variance ($\sum s_i + \sum s_{ij} = 0.4031$).

Discussion:

The black sea bass population abundance in the U.S. South Atlantic is declining and the current area of restored oyster reef is not sufficient in size to stabilize the black sea bass population growth rate. The results of this computer simulation model demonstrate that the population growth rate of black sea bass in the U.S. South Atlantic increased with increasing area of restored oyster reef. The mechanism for this increase was enhanced survival of estuarine-dependent juvenile stages in the presence of oyster reefs, and subsequent enhancement to fertility (see below). The strength of juvenile black sea bass recruitment may be strongly affected by the availability of appropriate habitat (NOAA TECHNICAL MEMORANDUM 2007), and previous studies have documented increased growth and survival of age-0 black sea bass in structurally complex habitats, including oyster reef (Arve 1960, Gwak et al. 2003, Scharf et al. 2006, Sullivan et al. 2006). Moreover, gut content analysis shows that age-0 black sea bass forage on oyster reef-associated prey, including amphipods, isopods, copepods and small fish. Increased availability of these prey species due to increased area of restored oyster reef may enhance growth rates (Lenihan et al. 2001). Previous research also shows that black sea bass density is higher on natural and restored oyster reefs compared to nearby sand bottom (Lenihan et al. 2001).

A total of 52 km^2 of restored oyster reef was necessary to stabilize the black sea bass population growth rate in the U.S. South Atlantic. Sensitivity analyses indicated that early age-class fertility and abundance, factors that are directly or indirectly influenced by oyster reefs, are the most important parameters determining the amount of oyster reef area necessary to stabilize the black sea bass population growth rate. While the presence of oyster reef directly enhances abundance of sea bass and other species (Peterson et al. 2003), it indirectly enhances fertility by improving growth and survival (Mercer 1989). Abundance, survival, and fertility also interact to influence the extent of restored oyster reef necessary to stabilize the population growth rate of black sea bass. This is not surprising since these parameters determine a given species' population growth rate. For this study, we used a constant natural mortality rate. While we realize that natural mortality varies with age, age-specific natural mortality data were not available, and the sensitivity analysis indicated that natural mortality was not an important factor determining the extent of restored reef area necessary to stabilize the black sea bass population growth rate.

The global sensitivity analysis used in this model provides a robust assessment of the most important parameters contributing to the outcome of this non-linear, non-monotonic model. Global sensitivity analyses are superior to local sensitivity analyses in such studies because local sensitivity analyses evaluate the output sensitivity relative to a particular point in the parameter space, but such precise points may not occur in nature. For example, if abundance is high, small changes in fertility may produce large changes in the extent of reef necessary to stabilize the black sea bass population. If abundance is low, however, varying fertility may not change the model outcome. Given uncertainty in both abundance and fertility, a local sensitivity analysis cannot accurately predict the effects of changes in either parameter on the extent of reef necessary to stabilize the black sea bass population growth rate (Zi et al. 2008). Global sensitivity analyses allow for the examination of non-linear and interactive input effects on the model output (Cariboni et al. 2007). RS-HDMR is an efficient method for performing global sensitivity. It is conceptually similar and produces very similar results to the Sobol' method (Ziehn and Tomlin 2009), which has been applied to ecological and systems biology models, but is less computationally expensive to perform (Aschoug et al. 2005, Cariboni et al. 2007, Marino et al. 2008; Ziehn and Tomlin 2009).

In addition to the global sensitivity analyses, the quadratic programming routine on bootstrap replicate time-series of the 1978-2004 time-series of black sea bass abundance reproduced the observed, 27-year time series with ~85% accuracy. In comparison, previous research using quadratic programming to estimate population demographic rates of sea lions reproduced observed time series with ~24% accuracy (Wielgus et al. 2008).

Our computer simulation model demonstrated that, regardless of the cost and benefit schedules or discount rates examined, oyster reef restoration was the most economically effective management option. This result was due, in part, to enhancement of other species, including gag grouper, gray snapper, sheepshead, and stone crab (Peterson et al. 2003). The life histories of these species make them especially good candidates for oyster reef-derived population enhancement for numerous reasons. For example, larval gag grouper settle out of the pelagic zone to inshore habitats rich in structural complexity, including oyster reefs (Heppel et al. 2006), with higher juvenile abundance on oyster reefs compared to nearby marsh and unvegetated habitats, and stomach contents dominated by oyster reef-associated prey for juvenile feeding (Zimmerman et al. 1989, Lenihan et al. 2001, Grabowski et al. 2005). In addition, gag grouper juvenile abundance in seagrass beds was strongly correlated with adult year class strength, suggesting that the availability of suitable juvenile habitat may be an important factor driving adult abundance (Allman and Grimes 2002).

Gray snapper spawn offshore (Powers et al. 2003), and individuals migrate into estuaries as young juveniles (Rutherford et al. 1989). Similar to gag grouper, gray snapper abundance is higher where structural complexity is greatest (Drew and Eggleston 2008), and are sometimes found only on restored and natural oyster reefs, and absent over soft sediment habitat (Lenihan et al. 2001). Gray snapper juveniles prey on reef associated species (Lenihan et al. 2001), and high juvenile site fidelity may contribute to their enhanced abundance via oyster reef restoration (Lara et al. 2008).

Sheepshead spawn offshore (Tremain et al. 2004) and settle in estuarine seagrass beds and mudflats (Munyandorero et al. 2006). Later stage juveniles (~40mm) migrate to structured estuarine habitats, including oyster reefs, where they congregate with adults

(Murphy and MacDonald 2000). Sheepshead juveniles feed on encrusting algae and reef-associated soft-bodied invertebrates until about 50mm TL, after which they feed on hard-bodied invertebrates including oysters (Murphy and MacDonald 2000, Lehnert and Allen 2002, Tolley et al. 2005). In field studies, juvenile sheepshead were more abundant on oyster reefs than nearby mud and sand habitat (Lehnert and Allen 2002, Plunket 2003, Tolley and Volety 2005).

Stone crab population dynamics are influenced by the presence of structurally complex habitat, and the presence of oyster shell and associated biomass decreased the mean time to metamorphose for stone crab larvae, indicating that the presence of suitable habitat is very important for post-larval settlement and subsequent habitat use (Krimsky and Epifanio 2008). Field studies show that shelter availability creates a demographic bottleneck for stone crab recruitment to adult age-classes (Beck 1995, 1997, Shervette et al. 2004), and post-settlement juveniles inhabit shallow structured habitat (Krimsky and Epifanio 2008). Juvenile stone crab abundance is higher on oyster reefs than nearby marsh or unvegetated habitat (Zimmerman et al. 1989). In field experiments, the addition of PVC to existing oyster reefs increased the size and density of stone crabs compared to control habitats (Shervett et al. 2004). Stone crab growth rates were also higher at sites supplemented with shelter, compared to sites which were not supplemented (Beck 1995, 1997). These factors help explain the sharp increase in stone crab density in the presence of oyster habitat (Peterson et al. 2003).

In general, primarily young-of-the-year fish are enhanced by oyster reef restoration because the majority of individuals inhabiting the reef are age-0 (Peterson et al. 2003). For example, tag recapture studies in the Mid-Atlantic Bite show higher juvenile black sea bass recapture rates during the summer than the fall, presumably when juveniles are moving from oyster reefs to the open ocean, suggesting that fish move off-reef at approximately 100 mm TL during the fall (Able and Hales 1997). This ontogenetic shift is further demonstrated by adult black sea bass' year-round association with continental shelf reefs (Powers et al. 2003). Although adult black sea bass are sometimes observed on oyster reefs (Lenihan et al. 2001), adults are considered transient reef visitors whereas juveniles tend to display high reef fidelity (NOAA TECHNICAL MEMORANDUM 2007).

Black sea bass and stone crab were the most important species driving the cost effectiveness of oyster reef restoration as a fisheries management tool. Our model did not evaluate spatial differences in the effectiveness of oyster reef restoration for black sea bass management. For example, oyster reefs built in areas where stone crab and black sea bass co-occur, such as Biscayne National Park, Florida and southeastern NC, would be expected to show the highest cost-effectiveness compared to regions where only one species occurs.

Ecosystem Effects of Oyster Reefs Not Considered in Our Model

This study considered only the benefits of oyster restoration to black sea bass and other reef inhabitants, such as gag grouper, gray snapper, sheepshead, and stone crab. Oyster reefs provide other ecosystem benefits, however, including enhanced oyster larval output to fished areas, improved water quality via filtration, and erosion control via near-shore and inter-tidal reefs. These additional benefits make our estimates of net economic benefits very conservative. Although quantitative estimates of the effectiveness of oyster reef restoration for enhancing the oyster fishery were not available, oyster reef restoration has the potential to increase oyster larval supply, thereby enhancing settlement and recruitment to the fishery (B. Puckett, NC State University, personal communication).

Oyster reefs also have the potential to improve water quality through water filtration, thereby reducing concentrations of nutrients, phytoplankton, suspended sediments, and bacteria (Langdon and Newell 1990, Nelson et al. 2004, Cerco and Noel 2005). A 10-fold increase in oyster biomass could equate to a 9-27% decrease in chlorophyll *a* concentrations; 7-10% decrease in nitrogen concentrations; 6-14% decrease in algal carbon biomass; 9-21% decrease in net primary production; 4.5-20% increase in dissolved oxygen; 13-33% decrease in light attenuation; and 21-43% increase in submerged aquatic vegetation biomass (Cerco and Noel 2005). Similar studies suggest that 25 grams dry weight/m^2 live oysters distributed evenly throughout a given area has the potential to reduce suspended sediment concentrations by an order of magnitude (Newell and Koch 2004). In flume and mesocosm studies, oysters changed the phytoplankton community composition, shifting dominance from chain-forming diatoms to rapidly growing diatoms, the latter of which have relatively high nutritional value (Pietros and Rice 2003).

Oyster reefs also provide shoreline erosion control. For example, the presence of oyster reefs change the energy flow of water as it moves over a reef, thereby reducing the energy of the water as it hits the shore (Coen and Luckenbach 2000). In addition, experiments in North Carolina and Louisiana demonstrate reduced shoreline erosion and accretion, and increased elevation, at sites with restored oyster reefs near shore compared to sites without restored oyster reefs (Meyer et al. 1997, Piazza et al. 2005). Beyond the direct benefits of oyster restoration to black sea bass and other species, the ecosystem benefits discussed above were not accounted for in our benefit calculations.

The size, geometry and location of oyster reefs within an estuarine landscape will likely impact their effectiveness at providing ecosystem services. For example, habitat edges and habitat patch size can have species- and size-specific influences on species interactions (Eggleston et al. 1999; Fagan et al. 1999). In oyster reef communities, small macrofauna abundance and overall species diversity were greater on large oyster patches than on small oyster patches (Eggleston et al. 1999), and previous research demonstrates that gag grouper and gray snapper size and abundance depend on habitat patch size (Lindberg et al. 2006 Valentine-Rose et al. 2007, Drew and Eggleston 2008). Oyster reef location may also be important for nekton utilization of oyster habitats. Species-specific salinity requirements (Tolley et al. 2005), location relative to tidal cycles (Lehnert and Allen 2002), and habitat type surrounding the reef (Grabowski et al. 2005) are important factors to consider when determining which species will benefit from a particular oyster reef habitat. Finally, reef size and placement also affects the function of oyster reefs for improving water quality and mitigating shoreline erosion. Physical conditions, such as flow, wave attenuation, dissolved oxygen, and reef height alter water filtration by changing oyster growth, survival, and filtration rates (Tenore and Dunstan 1973, Lenihan 1999, Barbier et al. 2008). In field experiments, wave attenuation rarely responds linearly to changes in nearshore habitat size (Barbier et al. 2008).

Our computer simulation model assumed that the fish and shellfish populations enhanced by oyster reef habitat, including black sea bass, gag grouper, gray snapper, sheepshead, and stone crab populations, will not experience intra-specific or inter-specific density-dependence as a result of reef restoration. Age-0 individuals in the population are added proportionally to oyster reef habitat, and thus age-0 density does not increase with increasing a reef area. Furthermore, the final black sea bass population size after the 30 year model period under the oyster reef restoration and reduced fishing mortality scenarios were 14.6 million 16.14 million individuals, respectively, while the 1978 population size was 27 million individuals (SEDAR 2005). Thus, even after oyster reef restoration, the population size of black sea bass will presumably not exceed habitat carrying capacity based on their population size in 1978.

Although our model showed that neither oyster reef restoration nor fishing mortality reduction caused the black sea bass population size to exceed the historic carrying capacity, ecological regime changes following steep declines in the population density over the last 35 years may affect the population's recovery (Baskett et al. 2006; Meyers and Worm 2005). For example, juvenile black sea bass share coastal habitats with numerous other species, such as pinfish and oyster toad fish, which are not as heavily exploited as black sea bass, and fill the juvenile black sea bass niche in its absence. In addition, Allee effects, which can occur at low population densities, may cause decreased reproduction in the already decimated population, therefore further hindering population recovery (Frank and Brickman 2000). Finally, depensatory mortality, in which juvenile survival declines at low population levels, may limit the effectiveness of reduced fishing mortality for black sea bass management (Frank and Brickman 2000). Oyster reef restoration enhances juvenile black sea bass survival, and may counteract possible juvenile depensatory mortality. Oyster restoration may provide insurance against negative density-dependent effects such as depensatory mortality and Allee effects on reproduction.

Costs of Oyster Restoration Relative to Other Habitats

Oyster population abundance has been declining for more than 100 years (Rothschild et al. 1994). Between 1890 and 1990, oyster production on the East coast of the United States declined from 160 million pounds per year to about 20 million pounds per year (Leonard 1993). In response to oyster population decline, and because of the economic and ecological importance of oysters, oyster reef restoration efforts have been underway for decades. For example, the North Carolina Division of Marine Fisheries (NCDMF) has created 9 no-take, sub-tidal oyster reserves that are intended to serve as broodstock sanctuaries (NCDMF). The North Carolina Coastal Federation (NCCF) leads a community-wide oyster restoration program whose purposes are to improve public awareness of the importance of oyster habitat, increase public participation in habitat restoration efforts, and protect water quality and restore oyster habitat (NCCF). In addition, the South Carolina Department of Natural Resources (SCNDR) facilitates a community-focused, volunteer-reliant inter-tidal oyster restoration effort to restore and monitor oyster habitats along the

South Carolina coast (SCDNR). In Georgia, the University of Georgia (UGA) Marine Extensions coordinates a community-based oyster reef restoration program, designed to enhance inter-tidal oyster reefs throughout the state (UGA). Finally, the Department of Agriculture and Consumer Services (DOACS) in Florida has begun oyster reef restoration efforts on the East Coast with the goal of maintaining and protecting productive oyster habitats (FLDOACS 2000). Although the current area of restored oyster reef is not sufficient to stabilize the population growth rate of black sea bass, ongoing oyster reef restoration efforts throughout North Carolina to Florida highlight important capabilities and infrastructure already in place to implement a ~52 km^2 oyster restoration. For example, using funding from the American Recovery and Reinvestmant Act to NOAA, ~0.5 km^2 of oyster reef will be restored in 18 months during 2009-10 in Pamlico Sound, NC (T. Miller, NC Coastal Federation, pers. comm.). Similarly, in the Chesapeake Bay, which once held at least 770 km^2 of oyster reef (McCormick-Ray 2005), ~50 km^2 of oyster reef was restored between 1990 and 2007 for a rate of ~ 3km^2/year (ORET 2009). Thus, at a rate of 3 km^2 of restored oyster reef/year/state the proposed oyster restoration of 52 km^2 could be conducted within the S. Atlantic within 5 years (3 km^2/year/state X 4 states X 5 years = 60 km^2).

In this study, oyster restoration will cost approximately \$10 million/km^2. This estimate is conservative compared to Chesapeake Bay oyster restoration programs, which cost approximately \$2.5-5.0 milion/km^2 (Henderson and O'Neil 2003). In addition, oyster reef restoration costs are moderate compared to other coastal habitat restoration. For example, coral reef restoration costs approximately \$159 million/km^2, and mangrove forest restoration costs between \$300,000 and \$510 million/km^2 depending on restoration methods. Soft substrate estuarine habitat restoration, including salt marsh and seagrass rehabilitation, cost between \$900,000 and \$16 million/km^2 (Spurgeon 1998).

Recent reauthorization of the Magnuson-Stevens Fisheries Conservation and Management Act (MS FCMA) requires the identification of essential fish habitat in fisheries management plans (NOAA 2007). Recognizing and prioritizing essential fish habitat requires (1) identifying sensitive life history stages through stage-structured models; (2) determining habitats important to those stages; and (3) locating habitat sites in which high densities of the species occurs (Levin and Stunz 2005). While local parameterization of this model would be required for site-specific decisions about oyster reef as essential fish habitat, this study and others fulfill MS FCMA requirements 1 and 2 above for black sea bass, and the collective results demonstrate that oyster reef restoration is a viable solution for stabilizing the black sea bass population (Peterson et al. 2003, this study).

Holistic management considers interactions among ecosystem components and achieves sustainability through adaptive management (Botsford et al. 1997). While much research has focused on the efficacy of protective habitat management, such as no-take marine reserves and marine protected areas (Kelleher 1996, Walters 2000, Gerber et al. 2002), little research has focused on the role of habitat restoration as a marine fisheries management tool (Turner et al. 1999). One example of habitat restoration as a fisheries management tool is a theoretical model of a species with separate fishing and spawning grounds, such as snappers or groupers (Mangel 2000). The results of the model show that loss of spawning habitat has the same effect on the species population size as increased fishing mortality, and that strategically placed reserves can help achieve fishery sustainability, even if fish do not migrate out of the reserve (Mangel 2000). Marine reserves may increase catch by 0.9 -2.6 metric tons km^{-2} year^{-1} by protecting fish from exploitation and improve fish habitat within the reserve (Rodwell et al. 2003). Finally, a five year experimental management program in northwestern Australia showed that catch of *Lethrinus* and *Lutjanus* fishes was maximized by ‘actively adaptive’ management, which included closing certain areas to fishing and opening others on a rotational basis (Turner et al. 1999).

The results of this study demonstrate that the extensive benefits of oyster reef restoration, including increased abundance of commercially and recreationally important fish and shellfish, contribute to the potential of oyster reef restoration as a cost-effective and holistic fisheries management tool. Further research is needed to examine the effects of species interactions to fully understand the impact of habitat restoration on target species. In addition, future research needs to address spatial differences among habitats and the effect of these differences on the efficacy of habitat restoration (e.g., Beck et al. 2003). Habitat restoration may provide an important alternative to traditional catch reduction for rebuilding and stabilizing marine fisheries populations.

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Table 1: (a) Black sea bass demographic data used to estimate the upper limit of fertility estimates. F denotes fecundity, or the average number of eggs per female in a given age-class. SL denotes the standard length (mm). TL denotes total length (mm). Parameter estimates are equal to (F)x(larval survival)x(proportion of females in an age-class)x(proportion of females mature in an age-class). (b) Total length (TL), proportion of females, and proportion of females mature in each age-class. Note that the proportion of mature females in age-0 is 0, so age-0 fertility is 0. Data adapted from SEDAR 2005.

(a)

Parameter	Estimates Available	Source	Estimate Used	Justification
F-SL Relationship	a)$\mathrm{Log}(F)=0.308+1.973\mathrm{Log}(SL)$ b)$\mathrm{Log}(F)=-2.10+3.03\mathrm{Log}(SL)$ c)$\mathrm{Log}(F)=-0.309+2.318\mathrm{Log}(SL)$	Mercer 1989	c) $\mathrm{Log}(F)=-0.309+2.318\mathrm{Log}(SL)$	Yields largest estimates
TL-SL Relationship	$TL = 1.35SL - 10.83$	SEDAR 2005	N/A	N/A
TL at Age	See Table 1B	SEDAR 2005	N/A	N/A
F	Calculated from estimates above			
Larval Survival	0.000001	Cowen et al. 2006	0.00001	Extra order of magnitude to account for uncertainty
Proportion females in age-class	See Table 1B	SEDAR 2005	N/A	N/A
Proportion females mature	See Table 1B	SEDAR 2005	N/A	N/A

(b)

Age-class	TL	Proportion Females Mature	Proportion Females
0	127	0	1
1	188.7	0.854	0.899
2	241.3	0.980	0.763
3	286.2	0.998	0.538
4	324.4	1	0.297
5	356.9	1	0.132
6	384.6	1	0.052
7	408.3	1	0.02
8	428.4	1	0.007
9	445.6	1	0.003
10	460.2	1	0.001
11	472.7	1	0.00001

Table 2: Calculations for estimating the age-specific abundance of black sea bass in the presence of restored oyster reef. R denotes the area of restored reef; N_i denotes 2004 age-specific abundance without the addition of restored oyster reef (SEDAR 2005), and N_i' denotes age-specific abundance in the presence of restored oyster reef. The value 0.39 is the number of fish added per fish added per 10 m^2 of restored oyster reef (Peterson et al. 2003). To calculate the number of fish added per 1 m^2, the reef area was divided by 10. The values for the 2004 N_i decrease with age because as each particular cohort passes from one age-class to the next, a proportion of individuals die.

Age-class	2004 N_i (No Reef)	N_i'
0	6406360	6406360+(0.39)(R/10)
1	4518540	$(N_0')(s_0)$
2	3053150	$(N_1')(s_1)$
3	2418930	$(N_2')(s_2)$
4	207048	$(N_3')(s_3)$
5	24407	$(N_4')(s_4)$
6	861	$(N_5')(s_5)$
7	105	$(N_6')(s_6)$
8	14	$(N_7')(s_7)$
9	1	$(N_8')(s_8)$
10	0	$(N_{9'})(s_9)$
11	0	$(N_{10}')(s_{10})$

Table 3: Age-specific survival of black sea bass during model years 1-12. Survival in the presence of the reef ($s_{i'}$) incrementally replaces survival derived from 1978-2004 age-specific abundance estimates (s_i) (SEDAR 2005, calculated above).

	Age-class											
Model Year	0	1	2	3	4	5	6	7	8	9	10	11
1	s_0	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
2	s_0'	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
3	s_0'	s_1'	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
4	s_0'	s_1'	S_2'	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
5	s_0'	s_1'	S_2'	s_3'	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}
6	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6	s_7	s_8	s_9	s_{10}	s_{11}
7	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	s_7	s_8	s_9	s_{10}	s_{11}
8	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	s_7'	s_8	s_9	s_{10}	s_{11}
9	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	s_7'	s_8'	s_9	s_{10}	s_{11}
10	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	s_7'	s_8'	s_9'	s_{10}	s_{11}
11	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	s_7'	s_8'	s_9'	s_{10}'	s_{11}
12	s_0'	s_1'	S_2'	s_3'	s_4'	s_5'	s_6'	$s_{7'}$	$s_{8'}$	$s_{9'}$	$s_{10'}$	$s_{11'}$

Table 4: Model parameter estimates and sources for Gag (gag grouper), GS (gray snapper), SH (sheepshead), and SC (stone crab). **E** denotes enhancement (individuals per km^2; Peterson et al. 2003), **M** denotes instantaneous natural mortality, *asp* denotes recruitment age, *csp* denotes proportion of total catch harvested by the commercial fishery, w*sp* denotes average kg/fish caught, v*sp* denotes the average dockside value (USD) per kg (NMFS 2004, 2007), rate*sp* denotes the species-specific exploitation rate (proportion of total population harvested annually), and ratio*sp* denotes the ratio of the number of individuals harvested in the recreational catch-and-consume fishery compared to the recreational catch-and-release fishery. Symbols denote data sources (see below)

Species	E	M	*asp*	*csp*	w*sp*	v*sp*	rate*sp*	ratio*sp*
Gag	1.6x10^4	0.14[*]	3[*]	0.436[*]	5.95kg/fish[*]	$6.18/kg	0.126[**]	0 [Φ]
GS	9.6x10^4	0.32[**]	4[†]	0.15[†]	1.79kg/fish[‡]	$4.95/kg	0.200[§§]	2.61[Θ]
SH	1.04x10^5	0.15[††]	1[††]	0.1[††]	0.88kg/fish[‡]	$1.66/kg	0.0411[††]	0.8957[Θ]
SC	2.577x10^5	0.35[‡‡]	2[§]	1[Φ]	0.13kg/crab[‡]	$9.62/kg	0.636 [Φ Φ]	0 [Φ]

[*]SEDAR 2006; [**]Burton 2001; [†]FWRI 2006; [‡]Calculated above; [††]Munyandorero et al. 2006l; [Φ]No data available; [‡‡]FWRI 2007; [§]Muller et al. 2006; [§§]SEDAR 2008; [Φ Φ]Ehradart et al. Die 1990; [Θ]NMFS 2006

Table 5. The net economic benefits of three black sea bass management scenarios: (i) Oyster reef restoration, (ii) Fishing mortality reduction, and (iii) Management inaction. In all cases, oyster reef restoration was the most econiomcally cost-effective option. Each scenario varied according to a specific combination of cost, benefit, and discount rate. **Scenario A:** Reef restoration costs occur at time 0, and benefits begin accruing immediately. Fishing mortality is reduced immediately. Discount rate=0.03, or 3% per year**. Scenario B:** Reef restoration costs occur at time 0, and benefits begin accruing immediately. Fishing mortality is reduced immediately. Discount rate=0.07, or 7% per year. **Scenario C:** Reef restoration benefits are delayed five years, and costs are phased in over five years. F reduction begins immediately. Discount rate =0.03, or 3% per year. **Scenario D:** Reef restoration benefits are delayed five years, and costs are phased in over five years. Fishing reduction begins immediately. Discount rate=0.07, or 7% per year. **Scenario E:** Reef restoration benefits and costs begin immediately, and F is reduced proportionally over the first 12 model years. Discount rate=0.03, or 3% per year. **Scenario F:** Reef restoration benefits and costs begin immediately, and F is reduced proportionally over the first 12 model years. Discount rate=0.07, or 7% per year. **Scenario G:** Reef restoration benefits are delayed five years, and costs are phased in over five years. F is reduced proportionally over the first 12 model years. Discount rate=0.03, or 3% per year. **Scenario H**: Reef restoration benefits are delayed five years, and costs are phased in over five years. F is reduced proportionally over the first 12 model years. Discount rate=0.07, or 7% per year. Bolded numbers indicate the management option which is the most economically effective; in eight out of eight cases, oyster reef restoration is yields the greatest net economic benefit. Italicized numbers indicate the management option with the greatest number of individuals in the population at the end of the 30 year model period. In eight out of eight timing scenarios, fishing mortality reduction results in the greatest final population size.

	Net Economic Benefit ($US)					
Scenario	Oyster Reef Restoration		Fishing Mortality Reduction		Management Inaction	
	Net Economic Benefit (USD)	Final Population Size (#Individuals)	Net Economic Benefit (USD)	Final Population Size (#Individuals)	Net Economic Benefit (USD)	Final Population Size (#Individuals)
A	**$1,356,400,000**	14,599,146	$549,836,000	*16,141,390*	$438,473,000	1,020,651
B	**$662,780,000**	14,599,146	$347,993,000	*16,161,390*	$298,586,000	1,020,651
C	**$1,095,600,000**	12,526,955	$549,836,000	*16,141,390*	$438,473,000	1,020,651
D	**$485,560,000**	12,526,955	$347,993,000	*16,161,390*	$298,586,000	1,020,651
E	**$1,356,400,000**	14,599,146	$423,993,000	*16,089,145*	$438,473,000	1,020,651
F	**$662,780,000**	14,599,146	$291,863,000	*16,089,145*	$298,586,000	1,020,651
G	**$1,095,600,000**	12,526,955	$423,993,000	*16,089,145*	$438,473,000	1,020,651
H	**$485,560,000**	12,526,955	$291,863,000	*16,089,145*	$298,586,000	1,020,651

$$\begin{bmatrix}
f_0 & f_1 & f_2 & f_3 & f_4 & f_5 & f_6 & f_7 & f_8 & F_9 & f_{10} & f_{11} \\
s_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \mathrm{s}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & s_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & s_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & s_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & s_5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & s_6 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & s_7 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_9 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_{10} & 0
\end{bmatrix}$$

Figure 1: The Leslie population projection matrix for estimating the population growth of black sea bass in response to oyster restoration along the U.S. South Atlantic coast. The parameter f_i represents age-specific fertility, and s_i represents age-specific survival.

Figure 2: The relationship between the mean percent differences between black sea bass survival and fertility parameters estimated with boot-strap sub-sampled time-series and the full (y-axis) 27 year times-series, and the number of years in each time-series (x-axis).

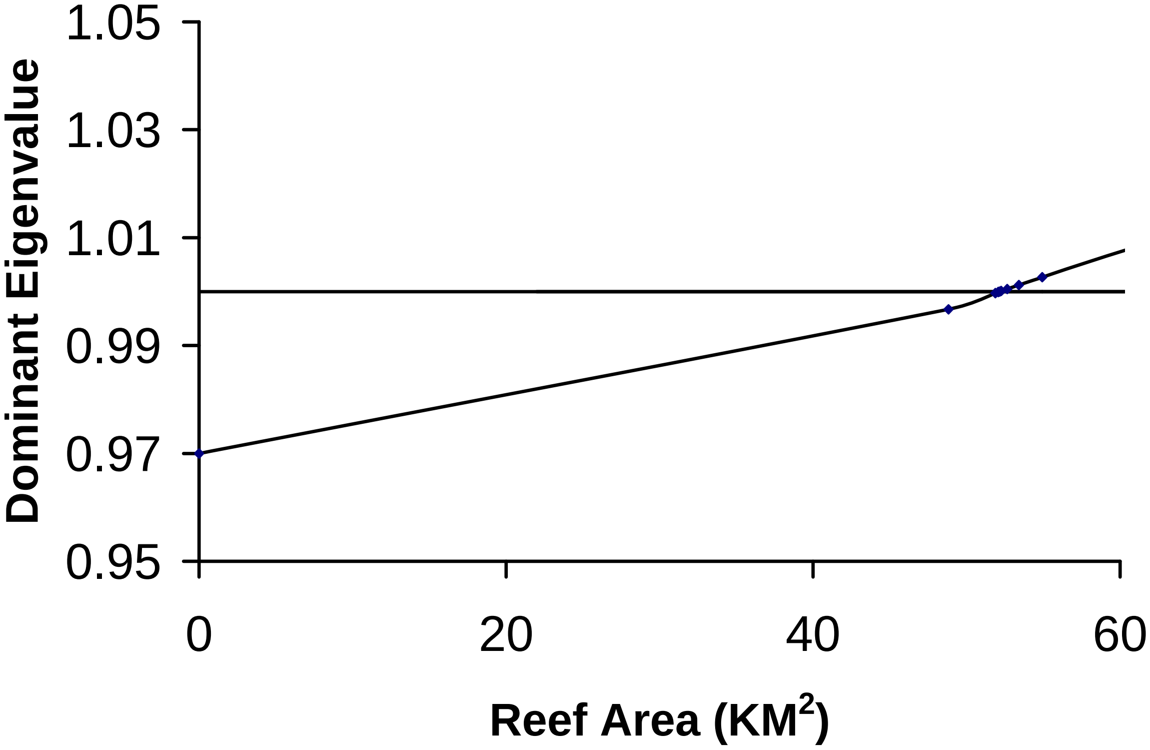

Figure 3: The relationship between the dominant eigenvalue (λ, y axis) of the black sea bass population and the area of restored oyster reef area (km^2, x axis). λ is an indication of population growth rate. The line at λ=1 indicates a stable population, while λ≤1 a shrinking population, and λ≥1 a growing population. A total of 52.166 km^2 restored oyster reef yields λ=1.

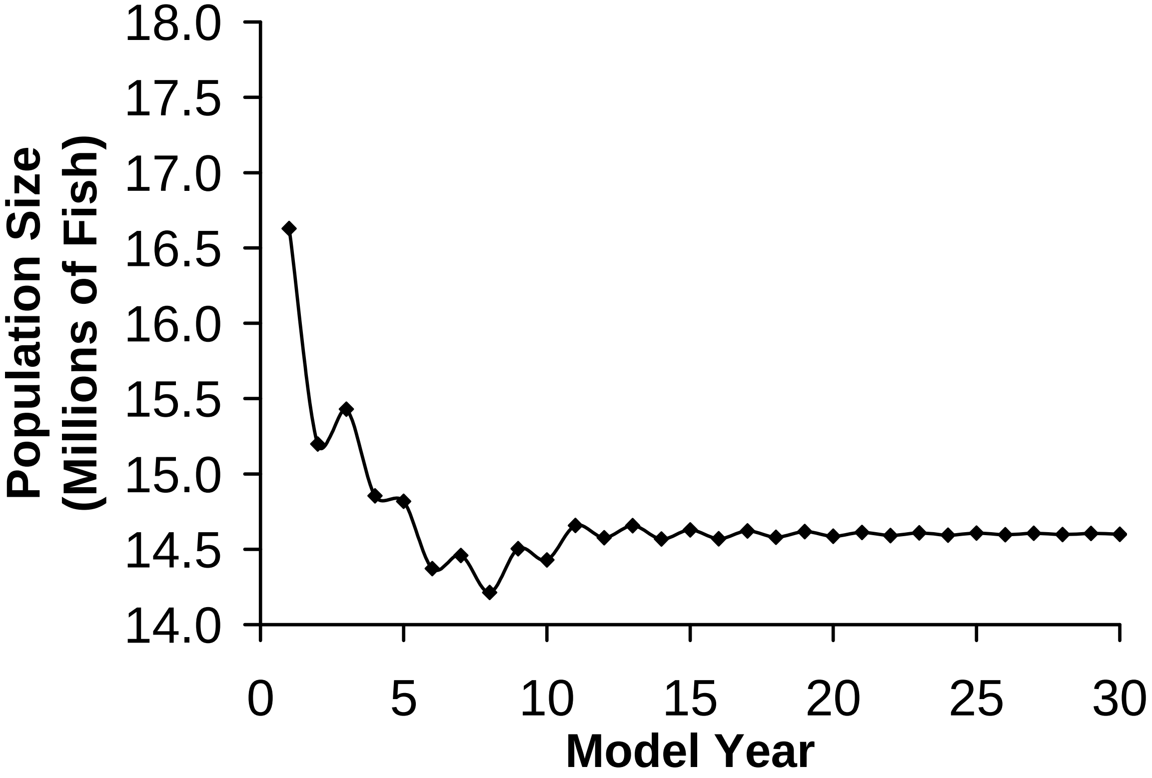

Figure 4: The black sea bass population size (number of individuals) as a function of model year under the oyster reef restoration scenario and immediate benefit schedule.

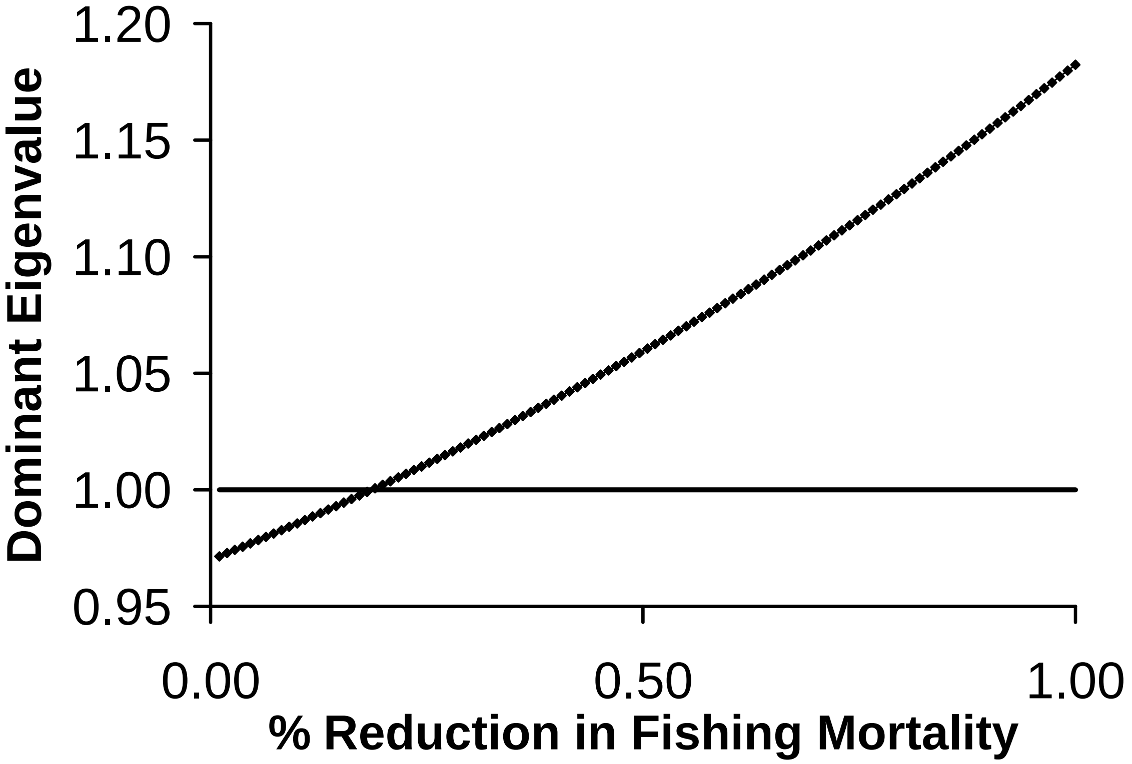

Figure 5: The relationship between the dominant eigenvalue (λ, y axis) of the black sea bass population and the percent reduction in fishing mortality. λ is an indication of population growth rate. The line at λ=1 indicates a stable population, while λ≤1 a shrinking population, and λ≥1 a growing population. A total of 52.166 km^2 restored oyster reef yields λ=1.

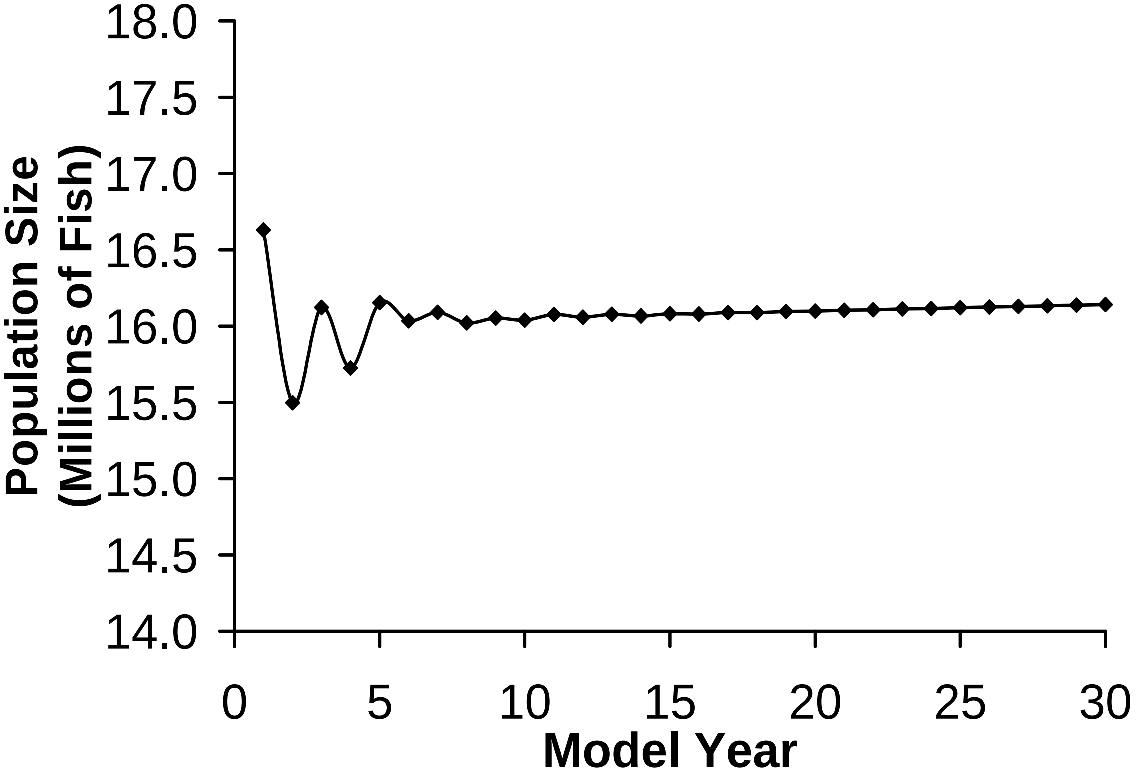

Figure 6: The black sea bass population size (number of individuals) as a function of model year under the fishing mortality (F) reduction scenario and immediate benefit schedule.

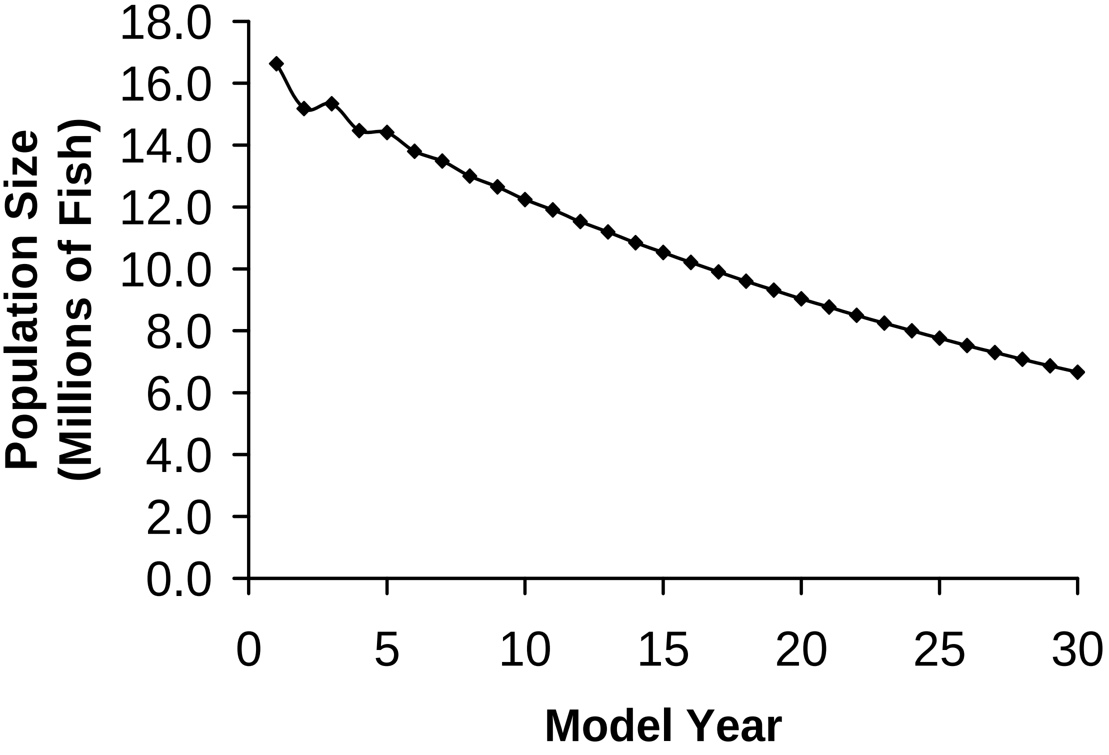

Figure 7: The black sea bass population size (number of individuals) as a function of model year under the management inaction scenario and immediate benefit schedule.

Appendices

Appendix 1: The parameter vector, and constraint matrix and vector used in the quadratic programming routine for estimating the black sea bass population parameters. The parameter vector **p** is constrained such that **Ap** ≤ **b**. (a) Parameter vector **p**. Age-0 fertility is not included because it is equal to zero (see Table 1(b)). (b) Constraint matrix **A** (c) Constraint vector **b**.

(a).

$$\begin{bmatrix} s_0 \\ f_1 \\ s_1 \\ f_2 \\ s_2 \\ f_3 \\ s_3 \\ f_4 \\ s_4 \\ f_5 \\ s_5 \\ f_6 \\ s_6 \\ f_7 \\ s_7 \\ f_8 \\ s_8 \\ f_9 \\ s_9 \\ f_{10} \\ s_{10} \\ f_{11} \end{bmatrix}$$

Appendix 1 Continued

$$\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

b.

Appendix 1 Continued

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 3.9277 \\ 6.7923 \\ 7.2950 \\ 5.3842 \\ 2.2906 \\ 1.4028 \\ 1.8611 \\ 0.2429 \\ 0.1141 \\ 0.0410 \\ 0.0436 \end{bmatrix}$$

c.

Appendix 2: MATLAB code used to perform the computer model simulation. (a) Model_Code.m (1) estimates the black sea bass abundance parameters, (2) calculates catch and the economic revenue derived from black sea bass commercial and recreational fishing under a management inaction scenario, (3) estimates the amount of restored oyster reef area necessary to stabilize the black sea bass population growth rate, (4) calculates catch under a reef restoration scenario, (5) calculates the economic revenue derived from commercial and recreational black sea bass catch under a reef restoration scenario, (6) calculates the catch, and economic benefit of commercial and recreational fishing of other reef-enhanced species, including sheepshead, gag grouper, gray snapper, and stone crab, (7) calculates the percent reduction in fishing mortality necessary to stabilize the black sea bass population growth rate, (8) calculates catch, and the economic value of black sea bass commercial and recreational fishing under a reduced fishing mortality scenario. (b) Monte_Carlo.m generates the Monte Carlo simulations used by the global sensitivity analysis software (available at http://www.gui-hdmr.de/method.html).

```
%%Erika Millstein, Script 1, Thesis Code, 2009
%%This code estimates (1) the black sea bass population demographic
%%parameters, (2) 2004 catch, (3) the revenue derived from black sea bass
%fishing under a management inaction scenario, (4) the extent of oyster
%reef neccesary to stabalize the population growth rate of black sea bass,
%(5) the cost of reef restoration and the revenue derived from black sea
%bass, gag grouper, gray snapper, sheepshead, and stone crab
%fishing under a reef restoration scenario, (6) the percent fishing
%mortality reduction neccesary to stabalize the population growth rate,
and
%(7) the benefit derived from black sea bass fishing under a fishing
%mortality reduction scenario.  Data sources are listed throughout



%%%%%STEP
ONE%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%ESTIMATING THE LESLIE MATRIX PARAMETERS FROM THE TIME SERIES (2005
BLACK
%%%SEA BASS SEDAR STOCK ASSESSMENT UPDATE

%The quadratic programming routine to estimate the parameters of the
Leslie
%Matrix for Black Sea Bass based on a time series (original) of
%abundance-at-age estimates. 'x' is the parameter vector, which is
reshaped into a 12x12 Leslie
%matrix 'a'.  The dominant eigenvalue of the 'a' is the "current"
%population growth rate of black sea bass (as of 2004).

%The abundance estimates 'original' come from from the
```

Appendix 2A Continued

```
%2005 stock assessment (SEDAR 2005) for years 1978-2004.  The code is
based on %the discussion and example of Wood's Quadratic Programming
method in %"Matrix Population Models: Construction, Analysis and
Interpretation"
%Edition 2 by Hal Caswell; Published by Sinaur Associates, Inc.
Publishers,
%Sunderland, MA, 2001 pps 144-149 (code adapted from example on pg. 148

%Abunance at age from 1978-2004 (2005 SEDAR Stock Assessment).
original=[10522600, 6831010, 5506280, 2812580, 1209810, 651957, 268240,
114552, 47032, 17696, 6285, 8826; 14868100, 7764340, 4785890, 2892790,
1431290, 596668, 318576, 129875, 55007, 22437, 8403, 7144; 11665300,
10781100, 5267360, 2344800, 1332980, 613628, 243571, 123684, 48197, 19696,
7830, 5308; 16551700, 8377890, 7159430, 2423150, 1001080, 521482, 223665,
82554, 39266, 14528, 5720, 3699; 10126100, 11796900, 5578130, 3575080,
1091650, 399091, 190292, 74539, 25356, 11305, 3993, 2491; 10552000,
9249540, 5358220, 3934970, 977988, 544329, 149467, 50908, 22577, 8286,
2677, 1790; 12499000, 7273070, 7691140, 2264030, 1325300, 363994, 123976,
54982, 20178, 6518, 25800, 1558; 10804900, 7809770, 6813200, 2072290,
1194120, 277982, 154676, 42472, 14466, 6416, 2354, 1269; 7508180, 7996000,
5753610, 3053760, 749010, 404048, 94032, 52322, 14367, 4893, 2170, 1226;
7357640, 5555400, 5892310, 3157060, 1416550, 326495, 176078, 40978, 22801,
6261, 2132, 1480; 8882310, 5446010, 4095710, 3025630, 1381460, 593723,
136818, 73786, 17172, 9555, 2624, 1514; 7306930, 6571630, 4008240,
1626650, 921627, 389671, 167415, 38579, 20806, 4842, 2694, 1167; 8057600,
5402470, 4829010, 1508230, 434058, 216488,    91482, 39304, 9057, 4885,
1137, 906; 5067850, 5950930, 3964520, 2099770, 425026, 98588, 49125,
20759, 8919, 2055, 1108, 464; 5100770, 3743210, 4369840, 1510300, 492937,
76764, 17786, 8862, 3745, 1609, 371, 284; 4851310, 3768190, 2751620,
1844580, 406186, 102961, 16016, 3711, 1849, 781, 336, 137; 9863940,
3583960, 2771730, 1197230, 527273, 95101, 24085, 3747, 868, 433, 183, 110;
6581610, 7279250, 2629800, 934009, 223835, 72705, 13096, 3317, 516, 120,
60, 40; 8149480, 4853550, 5329740, 723985, 124426, 20421, 6622, 1193, 302,
47, 11, 9; 5431190, 6013300, 3560890, 1922820, 115531, 10844, 1775, 576,
104, 26, 4, 2; 5366830, 4009420, 4416400, 1437290, 430531, 17521, 1642,
269, 87, 16, 4,   1; 5720080, 3966710, 2952760, 2215380, 472113, 103962,
4225, 396, 65, 21, 4, 1; 4394370, 4237510, 2925510, 2023300, 498939,
32119, 7017, 285, 27, 4, 1, 0; 6578780, 3255410, 3128770, 2035590, 519873,
71735, 4602, 1005, 41, 4, 1, 0; 5590490, 4873640, 2399370, 2110440,
238402, 29360, 4035, 259, 57, 2, 0, 0; 6099440, 4141520, 3598230, 1658530,
459731, 16295, 1991, 274, 18, 4, 0, 0; 6406360, 4518540, 3053150, 2418930,
207048, 24407, 861, 105, 14, 1, 0, 0];
original=original';

%Reformatting the abundance time series into a vector 'z'
z=original(:, 2:27);
z=z(:);
```

Appendix 2A Continued

```
%Format of the Leslie Matrix, with 1's in place of the paramater values.
%a(1,1) is 0 because fecundity is 0 for age 0 individuals
a=zeros(12,12);
a(1,:)=[0,1,1,1,1,1,1,1,1,1,1,1];
for y=1:11;
    a((y+1),y)=1;
end
%The non-zero entires in the parameter matrix, a
nonzero=(find(a));

%Generating matrix P(M in Caswell example)
P=[];
for t=1:26
  J=kron(original(:,t)', eye(12));
  m=J(:,nonzero);
  P=[P;m];
end;

%Generating the H and f vectors
H=P'*P;
f=-P'*z;

%Generating the inequality constraint matrix 'A' such that Ax<=b
A=zeros(44,22);
%-1 values in 'A' limit parameters to postive values
for r=1:22;
   A(r,r)=-1;
end
%1 values in 'A' designate parameters with upper bounds.  In other words,
%they act as place holders
A(23,1)=1;
A(24,3)=1;
A(25,5)=1;
A(26,7)=1;
A(27,9)=1;
A(28,11)=1;
A(29,13)=1;
A(30,15)=1;
A(31,17)=1;
A(32,19)=1;
A(33,21)=1;
A(34,2)=1;
A(35,4)=1;
A(36,6)=1;
A(37,8)=1;
A(38,10)=1;
A(39,12)=1;
A(40,14)=1;
```

Appendix 2A Continued

```
A(41,16)=1;
A(42,18)=1;
A(43,20)=1;
A(44,22)=1;

%Generating the inequality vector 'b' such that Ax<=b
b=zeros(44,1);
%1 values in 'b' provide an upper limit of 1 on survival parameters
for u=23:33;
     b(u,1)=1;
 end
%The next values in 'b' set upper limits on fecudnity paramterse.
%Constraints on fecundity are equal to
%(average fecudity at age)(porportion female at age)(porportion females
%mature at age)(average larval survival)(10).  Multiplying the product by
%10 acounts for uncertainty in the estimates.
%Average fecundity at age: Mercer 1989
%Porportion female and porportion female mature at age: SEDAR 2005
%Larval survival(0.000001): Wieglus et al 2007.
b(34,1)=3.9277;
b(35,1)=6.7923;
b(36,1)=7.2950;
b(37,1)=5.3842;
b(38,1)=2.2906;
b(39,1)=1.4028;
b(40,1)=1.8611;
b(41,1)=0.2429;
b(42,1)=0.1141;
b(43,1)=0.0410;
b(44,1)=0.0436;




%Calling MATLAB's quadratic programming function
[x]=quadprog(H,f,A,b,[],[],[],[],[],optimset('Largescale', 'off',
'display','off'));

%Generating the estimated projection matrix
a=zeros(144,1);
a(nonzero)=x;
a=reshape(a,12,12);

%Estimating the dominant eigenvalue (population growth rate proxy)
opts.disp=0;
eig=max(eigs(a,4,'LM',opts));

%Clearing unneeded variables to free up memory
```

Appendix 2A Continued

```
clear A H J P z expected m difference f b
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%STEP TWO.  DETERMINING THE CURRENT CATCH OF THE POPULATION (IN 2004)

 %Creating the vector of age-specific abundance in 2004 'N' from
'original'
N=original(:,27);

%Creating the vector of age-specific survival 's' from the paramaterized
Leslie
%matrix, 'a'
S=zeros(12,1);
for o=1:11
    S(o,1)=a(o+1,o);
end

%Creating the vector of age-specific natural mortality 'M'.  Constant
across
%ages (SEDAR 2005)
M=repmat(0.3,12,1);

%Creating the vector of fishing mortality 'F', from surival and natural
%mortality.
F=zeros(12,1);
F(:,1)=-M-log(S);
for q=1:12
if F(q,1)<0, F(q,1)=0;
end
end
F(12,1)=0;

meanF=zeros(1,30);
for times=1:30
    meanF(:,times)=mean(F);
end



%Creating the vector of age-specific catch 'C'
C=(N.*F).*(1-exp(-(F+M))).*/(F+M);
%Creating a matrix of age-specific catch, constant over a 30 year model
%period.  Catch stays constant throughout the model, so this matrix of
%constant catch will be used to calculate revenue derived from black sea
%bass fishing in the presence of the reef.
Ctotal=zeros(12,30);
for tt=1:30
    Ctotal(:,tt)=C(:,:);
```

Appendix 2A Continued

```
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%STEP THREE: DETERMING CATCH AND REVENUE UNDER A
MANAGEMENT INCATCION SCENARIO

%A three percent discount rate 'rate' is applied to account for consumers
desire
%to consume now rather than later.
rate=0.03;
%'value' is the value of black sea bass catch in price per fish
(calculated
%from NMFS)
value=1.55955378;
%'valuerec' is the black sea bass recreational value (cost)(fish^-1)(day^-
1).
%(EPA 2004)
valuerec=5.30;
%'numdaysrec' is the average number of black sea bass recreational fishing
%days (EPA 2004)

%'futureabundance' is the age-specific annual abundance under management
%inaction
futureabundance=zeros(12,30);
%'futurecatch' ist he age-specific annual catch under management inaction
futurecatch=zeros(12,30);
%'porportioncomm' is the average porportion of total harvest taken by the
%commerical fishery
porportioncomm=0.542425258;
%calculating the commercial 'commercialrevenuenothing' and
%recreational'recrevenuedoingnothing' under management inaction
commercialrevenuenothing=zeros(1,30);
reccatchlost=zeros(1,30);
recrevenuedoingnothing=zeros(1,30);
for year=1:30
    futureabundance(:,year)=a^year*original(:,27);
    futurecatch(:,year)=futureabundance(:,year).*F.*(1-S)./(F+M);
    recrevenuedoingnothing(:,year)=(sum(futurecatch(:,year)*(1-
porportioncomm)*(valuerec+value)*(1/(1+rate)^year)))+(sum(futurecatch(:,ye
ar)*(1-porportioncomm)*valuerec*3.78*(1/(1+rate)^year))); %3.78 bc catch
and release accounts for that many more fish than catch and harvest

commercialrevenuenothing(:,year)=sum(futurecatch(:,year)*porportioncomm*va
lue*(1/(1+rate)^year));
end
%calculating the total annual catch under managvement inaction
totalfuturecatch=sum(futurecatch);
%The total commercial ('commercial_revenue_doing_nothing) and recreational
```

Appendix 2A Continued

```
%(recreational_revenue_doing_nothing), and the total revenue of management
%inaction ('total_nothing')
commercial_revenue_doing_nothing=sum(commercialrevenuenothing);
recreational_revenue_doing_nothing=sum(recrevenuedoingnothing);
total_nothing=(commercial_revenue_doing_nothing)+(recreational_revenue_doi
ng_nothing);





%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%STEP 4:  DETERMINING THE AREA OF REEF (METERS SQUARED) NECCESARY FOR THE
%BLACK SEA BASS POPULATION DOMINANT EIGENVALUE=1

%The area of reef needed is determined using a search method which starts
%in the median between the highest ('max_reef_area')and lowest
('min_reef_area')possible reef area and determines the dominant
eigenvalue.
%If the eigenvalue is less than one ('desired_eigenavlue'), the program
next guesses the median between the first guess and the highest
%possible area, and it is mor than one, it guesses the median between the
first
%guess and the lowest possible area.  This continues until the appopriate
area is identified.  'area_guess' is the reef area for which
%the eigenvalue is currently being determined, and 'eigsreef' is the
%eigenvalue of the matrix under 'area_guess'
min_reef_area=1;
max_reef_area=100000000000;
desired_eigenvalue=1;

iterations=1;
eigsreef=-999; %unimportant starting value so while loop will work

area_guess=max_reef_area-((max_reef_area-min_reef_area)/(2^iterations));

while (round(eigsreef*10000)/10000) ~= desired_eigenvalue

   iterations=iterations+1;
   %x is the reef area yielding an eigenvalue of 1, once the while loop
has
   %completed.
   x=area_guess;
   Area(iterations,1)=x/(1000)^2;
   %Reef enhancement, or the number of indivduals per m^2 added as a
result
```

Appendix 2A Continued

```
   %of restored oyster reef (Peterson 2003)
   enhance=0.39/10;

    %Creating the vector of age-specific abundance in the presence of the
reef ('Nreef').  The reef
    %enhancement is added to the first age group, and the age 0 population
is
    %moved through the age-classes. 'S''Nreef' in age class t equals
    %'Nreef' in age class t+1.  'S is survival.
       Nreef=zeros(12,1);
    Nreef(1,1)=N(1,1)+(x*enhance);
    for e=2:12;
        Nreef(e,:)=Nreef((e-1),:)*S((e-1),:);
    end

    %Catch is held constant with increasing reef area, since the objective
of
    %the study is to determine the reef area neccesary to restore the
    %population without reducing catch.  In order to determine fishing
    %mortality in the presence of the reef ('Freef'), the 'Freef' wich
minimizes the squared difference
    %between catch without reef and catch with reef is determined using in
an
    %interative optimization program called patternsearch.  Patternsearch
is
    %part of MATLAB's Genetic Algorithm and Direct Search Toolbox.

%(http://www.mathworks.com/access/helpdesk/help/pdf_doc/gads/gads_tb.pdf)

    %Objfun is the sum of the difference squared, totaled over all age
classes, and is the scalar value which will be minimized.
    objfun=@(Freef) sum((C-((Nreef.*Freef).*(1-exp(-
(Freef+M)))./(Freef+M))).^2);

    %Creating the vectors of parameters to be used by the patternsearch
function
    %'lb' and 'ub' are the vectors of upper and lower bounds of 'Freef',
    %respectively.  x0 is the function starting point ('F' or fishing
    %mortality without the presence of restored oyster reef).
   x0=F;
   lb=repmat(0,12,1);
   ub=repmat(100,12,1);

[Freef,fval,exitflag]=patternsearch(objfun,x0,[],[],[],[],lb,ub,[],psoptim
set('Display','off','TolCon', 1e-10000));

   %Creating the vector of age-specific survival in the presence of the
reef 'Sreef',
```

Appendix 2A Continued

```
%based on M and Freef
    Sreef=exp(-(Freef+M));
   %Constraints on 'Sreef'
if (S(11,1)<0.001 && Sreef(11,1)>0.74069);
        Sreef(11,1)=0;
    end
    if (S(12,1)<0.001 && Sreef(12,1)>0.74069);
        Sreef(12,1)=0;
    end

    %Constructing the population matrix in the presence of the reef
    %('areef')
    areef=zeros(12,12);
    areef(1,:)=a(1,:);
    for s=1:11
        areef(s+1,s)=Sreef(s,1);
    end

    %Calculating the dominant eigenvalue of 'areef' ('eigsreef')
    opts.disp=0;
    eigsreef=max(eigs(areef,4,'LM',opts));
    Eigsreef(iterations,1)=eigsreef;
    %Determining the next reef area to try('area_guess')
    if eigsreef < desired_eigenvalue
        area_guess = area_guess+((max_reef_area-
min_reef_area)/(2^iterations));
    else
        area_guess = area_guess-((max_reef_area-
min_reef_area)/(2^iterations));
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%STEP FIVE: DETERMING THE COST AND REVENUE OF THE REEF

%%%Step 5A: Estimating population parameters for the first 12 years of the
%%%model.  Since the age span of black sea bass is 12 years, it will take
%%%12 years from the end of reef building for every age class to
%%%experience, and therefore benefit from, their first year on the reef.
%%%During the first 12 years, survival for individuals in the age class
%%%incrementally changes from survival without the reef to survival with
%%%the reef.  For example, during year one, only age class 0 survival
%%%equals 'Sreef' and survival for all other age classes equals 'S'.
During
%%%year 10, survival for age classes 0-9 is 'Sreef' and survival for age
%%%classes 10 and 11 is 'S'
```

Appendix 2A Continued

```
%'Sreefstep' is age-specific survival during model years 1-12 in the
presence of the
%reef.
Sreefstep=zeros(12,11);
%'areefstep' is the Leslie matrix for the current model year, such that a
%new matrix is constructed for model years 1-12.
areefstep=a;
%'abundancestep' is the age-specific abundance caluclated for model years
%1-12.  'abundancestep' for model year t+1 is the product of 'areefstep'
at time t and 'abundancestep' at time t.
%Abundance during model year one 'abundancestep(:,1)' is the 2004 age
%specific abundance (see above)
abundancestep=zeros(12,12);
abundancestep(:,1)=original(:,27);

for time=1:11
    areefstep(time+1,time)=Sreef(time,1);
    Sreefstep=[areefstep(2,1); areefstep(3,2); areefstep(4,3);
areefstep(5,4); areefstep(6,5); areefstep(7,6); areefstep(8,7);
areefstep(9,8); areefstep(10,9); areefstep(11,10); areefstep(12,11); 0];
    abundancestep(:,time+1)=areefstep*abundancestep(:,(time));
end

%'totalabundancestep' is the total annual abundance during model years 1-
12
%in the persence of the reef
totalabundancestep=sum(abundancestep);

%Creating a vector of age-specific annual abundance for model years 1-30
%('N_with_reef') and total abundance for model years 1-30
%('Total_N_with_reef').
N_with_reef=zeros(12,30);
Total_N_with_reef=zeros(1,30);
for y1=1:12
    N_with_reef(:,y1)=abundancestep(:,y1);
    Total_N_with_reef(:,y1)=totalabundancestep(:,y1);
end

for y=13:30
    N_with_reef(:,y)=areef^y*abundancestep(:,12);
    Total_N_with_reef(:,y)=sum(N_with_reef(:,y));
end



%%%STEP 5B: CALCULATING THE COST AND BENEFIT OF THE REEF
```

Appendix 2A Continued

```
calculating the cost of the reef ('costreef').  'x' is the total reef
%area in square meter, and 1415252.74 is the cost per square km (Stopher
%Slade, NCDMF, personal communication)
costreef=(x/1000^2)*10237594;
%annual commercial ('comrevenuereef'), and recreational ('recrevenuereef')
%revenue derived from black sea bass under the reef scenario.
commrevenuereef=zeros(1,30);
recrevenuereef=zeros(1,30);
%Applying a 3% annual discount rate ('rate')
for yearss=1:30

commrevenuereef(:,yearss)=sum(Ctotal(:,yearss))*porportioncomm*value*(1/(1
+rate)^yearss);
    recrevenuereef(:,yearss)=(sum(Ctotal(:,yearss)*(1-
porportioncomm)*(valuerec+value)*(1/(1+rate)^yearss)))+(sum(Ctotal(:,years
s)*(1-porportioncomm)*(valuerec)*(3.78)*(1/(1+rate)^yearss)));

end
%the total revenue of black sea bass commerical
%('bsb_commercial_benefit_of_reef), recreational,
%('bsb_rec_benefit_or_reef') and combined commercial and recreational
%('total_reef') under the reef restoration scenario over the 30 year model
%period.
bsb_commercial_benefit_of_reef=sum(commrevenuereef)
bsb_rec_benefit_of_reef=sum(recrevenuereef)
total_reef=(bsb_commercial_benefit_of_reef)+(bsb_rec_benefit_of_reef);



%%%STEP 5C: CALCULATING THE BENEFIT OF THE REEF FOR OTHER SPECIES
%variable definitions are self explanatory, or explained in comments.
Data sources are listed

%Sheepshead
sh_enhancement=1.04/10; %1.04 fish per 10 meters squared reef from
Peterson et al 2003
sh_added_year_one=sh_enhancement*x;
sh_M=0.15; %Sheepshead natural mortality, from  Munyandorero et al 2006
sh_age_fishable=1; %Munyandorero et al 2006
sh_added_to_fishery=sh_added_year_one*(exp(-
(sh_M))^sh_age_fishable)*0.1;%porgy exploitation rate
sh_porportion_commercial=0.1; %Munyandorero et al 2006
sh_added_to_commercial_catch=sh_porportion_commercial*sh_added_to_fishery;
sh_added_to_rec_catch=(1-sh_porportion_commercial)*sh_added_to_fishery;
sh_released=sh_added_to_rec_catch*.8957; %.895x as many fish are caught
and released as caught and harvested
sh_price_kg=1.657048924; %Munyandorero et al 2006
sh_avg_kg_fish_caught=0.871431873; %NMFS
sh_price_per_fish=sh_price_kg*sh_avg_kg_fish_caught;
```

Appendix 2A Continued

```
sh_added_value_commercial_catch=sh_price_per_fish*sh_added_to_commercial_c
atch;
sh_added_value_rec_catch=((valuerec+sh_price_per_fish)*sh_added_to_rec_cat
ch)+(sh_released*valuerec);
sh_comm_annual_net_pres_value=zeros(30,1);
sh_rec_annual_net_pres_value=zeros(30,1);

%Gag Grouper
gag_enhancement=0.16/10; %0.16 fish per 10 meters squared reef, from
Peterson et al 2003
gag_added_year_one=gag_enhancement*x;
gag_M=0.14; %Gag natural mortality, from  SEDAR 2006
gag_age_fishable=3; %SEDAR 2006
gag_added_to_fishery=gag_added_year_one*(exp(-
(gag_M))^gag_age_fishable)*0.0992; %proportion harvested;
gag_porportion_commercial=0.436; %SEDAR 2006
gag_added_to_commercial_catch=gag_porportion_commercial*gag_added_to_fishe
ry;
gag_added_to_rec_catch=(1-gag_porportion_commercial)*gag_added_to_fishery;
gag_price_kg=6.181070658; %NMFS
gag_avg_kg_fish_caught=5.95339986 ; %SEDAR 2006
gag_price_per_fish=gag_price_kg*gag_avg_kg_fish_caught;
gag_added_value_commercial_catch=gag_price_per_fish*gag_added_to_commercia
l_catch;
gag_added_value_rec_catch=gag_added_to_rec_catch*(valuerec+gag_price_per_f
ish);
gag_comm_annual_net_pres_value=zeros(30,1);
gag_rec_annual_net_pres_value=zeros(30,1);

% %Gray Snapper
GS_enhancement=0.96/10; %0.96 fish per 10 meters squared reef, from
Peterson et al 2003
GS_added_year_one=GS_enhancement*x;
GS_M=0.32; %Gag natural mortality, from Burton 2001
GS_age_fishable=4; %FRWI 2006 (Florida Fish and Wildlife)
GS_added_to_fishery=GS_added_year_one*(exp(-(GS_M))^gag_age_fishable)*0.1;
GS_porportion_commercial=0.15; %FRWI 2006
GS_added_to_commercial_catch=GS_porportion_commercial*GS_added_to_fishery;
GS_added_to_rec_catch=(1-GS_porportion_commercial)*GS_added_to_fishery;
GS_released=GS_added_to_rec_catch*2.691; %2.691 as many fish are caught
and released as harvesetd
GS_price_kg=4.947926928; %NMFS
GS_avg_kg_fish_caught=1.787862; %NMFS
GS_price_per_fish=GS_price_kg*GS_avg_kg_fish_caught;
GS_added_value_commercial_catch=GS_price_per_fish*GS_added_to_commercial_c
atch;
GS_added_value_rec_catch=(GS_added_to_rec_catch*(valuerec+GS_price_per_fis
h))+(GS_released*valuerec);
```

Appendix 2A Continued

```
GS_comm_annual_net_pres_value=zeros(30,1);
GS_rec_annual_net_pres_value=zeros(30,1);
%
% %Stone Crab
SC_enhancement=25.77/10; %0.96 fish per 10 meters squared reef, from
Peterson et al 2003
SC_added_year_one=SC_enhancement*x;
SC_M=0.35; %SC natural mortality, FWRI 2007
SC_age_fishable=2; %FRWI 2007 (Florida Fish and Wildlife)
SC_added_to_fishery=SC_added_year_one*(exp(-(SC_M))^SC_age_fishable)*.05;
SC_porportion_commercial=1; %No data on Rec Fishery available.  1 is an
assumption
SC_added_to_commercial_catch=SC_porportion_commercial*SC_added_to_fishery;
SC_added_to_rec_catch=(1-SC_porportion_commercial)*SC_added_to_fishery;
SC_price_kg_claw=9.626011194; %NMFS
SC_kg_per_claw=0.099692051; %NMFS(2004-2005 kgs landed/2004-2005 claws
landed)
SC_claw_per_crab=1.26; %FRWI 2007
SC_price_per_crab=SC_price_kg_claw*SC_claw_per_crab*SC_kg_per_claw;
SC_added_value_commercial_catch=SC_price_per_crab*SC_added_to_commercial_c
atch;
SC_comm_annual_net_pres_value=zeros(30,1);





%Calculating the net present value of sheepshead, gag grouper, gray
%snapper, and sheepshead recreational ('xx_rec_annual_net_pres_value') and
commerical (xx_comm_annual_net_present_value)
%revenue for each model year
for year=1:30

sh_comm_annual_net_pres_value(year,1)=sh_added_value_commercial_catch*(1/(
1+rate)^year);

sh_rec_annual_net_pres_value(year,1)=sh_added_value_rec_catch*(1/(1+rate)^
year);

gag_comm_annual_net_pres_value(year,1)=gag_added_value_commercial_catch*(1
/(1+rate)^year);

gag_rec_annual_net_pres_value(year,1)=gag_added_value_rec_catch*(1/(1+rate
)^year);

GS_comm_annual_net_pres_value(year,1)=GS_added_value_commercial_catch*(1/(
1+rate)^year);
```

Appendix 2A Continued

```
GS_rec_annual_net_pres_value(year,1)=GS_added_value_rec_catch*(1/(1+rate)^
year);

SC_comm_annual_net_pres_value(year,1)=SC_added_value_commercial_catch*(1/(
1+rate)^year);
end
%calculating the total (over all model years) net present value of
%sheepshead, gag grouper, gray snapper, and stone crab recreational
('xx_comm_net_present_value') and
%commerical catch ('xx_comm_net_present_value')
sh_total_comm_net_present_value=sum(sh_comm_annual_net_pres_value)
sh_total_rec_net_present_value=sum(sh_rec_annual_net_pres_value)
gag_total_comm_net_present_value=sum(gag_comm_annual_net_pres_value)
gag_total_rec_net_present_value=sum(gag_rec_annual_net_pres_value)
GS_total_comm_net_present_value=sum(GS_comm_annual_net_pres_value)
GS_total_rec_net_present_value=sum(GS_rec_annual_net_pres_value)
SC_total_comm_net_present_value=sum(SC_comm_annual_net_pres_value)
%calcualting the total commercial benefit of the reef
%('comm_benefit_of_reef)

comm_benefit_of_reef=sh_total_comm_net_present_value+gag_total_comm_net_pr
esent_value+GS_total_comm_net_present_value+SC_total_comm_net_present_valu
e+bsb_commercial_benefit_of_reef;



%calculating the total recreational benefit of the reef
%('rec_benefit_of_reef'_
rec_benefit_of_reef=sh_total_rec_net_present_value+gag_total_rec_net_prese
nt_value+GS_total_rec_net_present_value+bsb_rec_benefit_of_reef;

%calculating the total benefit of the reef ('total_benefit_of_reef')
total_benefit_of_reef=comm_benefit_of_reef+rec_benefit_of_reef;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%STEP SIX: DETERMING THE FISHING MORTALITY REDUCTION NECCESARY
TO ACHIEVE AN EIGENVALUE OF 1

%%%The porportion reduction needed is found using a serach mdethod. The
program starts at a median porportion fishing
%%%reduction between a minimum reduction ('min_red) and a maximum
reduction (max_red_), and calcualtes the dominant eigenvalue
%%%of the Leslie matrix with this reduction.  If the eigenvalue is more
%%%than one, it guesses the median between 0.01 and the first guess, and
if
```

Appendix 2A Continued

```
%%%the eigenvalue is less than one, it guesses the median between the
first
%%%guess and 1.  This continues until the appropritate porportion fishing
%%%mortality reduction is identified.  The 'desired_eigenvalue' is one
%%%becuase this represents a stable population growth rate.  'red_guess'
is
%%%the current fishing mortality reduction guess, which is being used to
%%%calculate the dominant eigenvalue.

min_red=.01;
max_red=1;
desired_eigenvalue_red=1;

iterationss=1;
eigsred=-999; %unimportant starting value so while loop will work

red_guess=max_red-((max_red-min_red)/(2^iterationss));

while (round(eigsred*1000)/1000) ~= desired_eigenvalue_red

iterationss=iterationss+1;

%Because it takes 12 years to realize the full benefits of restored oyster
%reef, fishing mortality reduction takes place over a 12 year period as
%well.  Fishing mortality is reduced incremetally, so that in model year
1,
%1/12 of the total reduction is implimented (if the reduction is 50%, then
%in model year one, the reduction is 4.16%) and in model year 12, the
total
%reduction is implimented (50% reduction)
%'Red' is the annual porportion fishing mortality reduction during model
%years 1-12.
reduction=red_guess;
Reduction(iterationss,1)=red_guess;
Red=zeros(12,1);
for p=1:12
    Red(p,1)=(red_guess/12)*p;
end

%Calculating a matrix of age-specific fishing mortality ('Fred') during
model years
%1-12, based on the incremental reduction.
Fred=zeros(12,30);
for c=1:12;
    for j=1:12;
        Fred(j,c)=(F(j,1)*(1-(Red(c,1))));
    end;
```

Appendix 2A Continued

```
end;

%Calculating age-specific survival ('Sred') during model years 1-12
Sred=exp(-(Fred+.3));
Sred(12,:)=0;
%Calculating the fishing mortality ('Fredfull') and survival ('Sredfull')
%for model years 13-30.  0.3 is natural mortality (SEDAR 2005).
Fredfull=F.*(1-reduction);
for jj=13:30
    Fred(:,jj)=Fredfull;
end

Sredfull=exp(-(Fredfull+0.3));
%Creating the Leslie Matrix ('aredfull') for model years 12-30.
aredfull=zeros(12,12);
aredfull(1,:)=a(1,:);
for d=1:11
    aredfull(d+1,d)=Sredfull(d);
end
%calculating the eigenvalue under the reduced fishing mortality scenario
%('eigsred').
pts.disp=0;
eigsred=max(eigs(aredfull,4,'LM',opts));
Eigsred(iterationss,1)=eigsred;
%Determining the next fishing mortality reduction to try ('red_guess').
if eigsred < desired_eigenvalue_red
        red_guess = red_guess+((max_red-min_red)/(2^iterationss));
else
        red_guess = red_guess-((max_red-min_red)/(2^iterationss));

end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%STEP SEVEN: CALCULATING THE BENEFITS OF REDUCED
FISHING MORTALITY


%%%STEP 7A: CALCULATING ABUNDANCE ('Nred') AND CATCH ('Cred') FOR MODEL
%%%YEARS 1-30


%Calculating the population size for years 1-12 of the model ('Nred') from
%the annual Leslie matrix in the presence of reduced fishing mortality
%during model years 1-12 (ared)
ared=zeros(12,12);
ared(1,:)=a(1,:);
```

Appendix 2A Continued

```
Nred=zeros(12,30);
%Forming the new Leslie Matrix for each of the 12 years, and determining
%age-specific abundance for each year
    for l=1:12
    for k=1:11
     ared(k+1,k)= Sred(k,l);
    end
    Nred(:,l)=ared^(l)*original(:,27);
    end

for g=13:30
Nred(:,g)=aredfull^(g-12)*original(:,27);
end
% %Calculating total catch at age for model years 1-12
Cred=zeros(12,30);
 for v=1:30;
 for h=1:12;
 Cred(h,v)=Nred(h,v)*Fred(h,v)*(1-Sred(h,v))/(Fred(h,v)+0.3);
 end;
 end;



%%%STEP 7B: CALCULATING BENEFIT

%Calculating the annual commerical ('comrevenueredf'), total commerical
('comm_benefit_reducing_f), annual recreational
%('recrevenueredf'), total recreational ('rec_benefit_reducing_f'), and
total combined commerical and recreational('total_f_red'),
%revenue derived from black sea bass under the fishing mortality scenario.
commrevenueredf=zeros(1,30);
recrevenueredf=zeros(1,30);
%Applying a 3% annual discount rate ('rate')
for years=1:30

commrevenueredf(:,years)=sum(Cred(:,years))*porportioncomm*value*(1/(1+rat
e)^years);
    recrevenueredf(:,years)=sum(((Cred(:,years)*(1-
porportioncomm)))*(valuerec+value)*(1/(1+rate)^years))+(sum(Cred(:,years)*
(1-porportioncomm)*(valuerec)*(1/(1+rate)^years)*(3.78)));
end

 comm_benefit_reducing_F=sum(commrevenueredf);
 rec_benefit_reducing_F=sum(recrevenueredf);
 total_f_red=(comm_benefit_reducing_F)+(rec_benefit_reducing_F);
```

Appendix 2A Continued

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%COST BENEFIT COMPARISON
Reef_Benefit=total_benefit_of_reef
Reef_Cost=costreef
Net_Benefit_of_Reef=Reef_Benefit-Reef_Cost
F_Reduction_Benefit=total_f_red
Inaction_Benefit=total_nothing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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http://www.sefsc.noaa.gov/sedar/. (May 2009).
```

Appendix 2A Continued

%SEDAR. 2006. Stock assessment report: South Atlantic gag grouper. South Atlantic Fisheries Management Council SEDAR 10 Stock Assessment Report 1. Available: http://www.sefsc.noaa.gov/sedar/. (May 2009).

%Wielgus, Jeffrey, Ford Ballantyne IV, Enric Sala, and Leah Gerber. 2007. Viability analysis of reef fish populations based on limited demographic data. Conservation Biology 21(2):447-454.

Appendix 2B

```
original=[10522600, 6831010, 5506280, 2812580, 1209810, 651957, 268240,
114552, 47032, 17696, 6285, 8826; 14868100, 7764340, 4785890, 2892790,
1431290, 596668, 318576, 129875, 55007, 22437, 8403, 7144; 11665300,
10781100, 5267360, 2344800, 1332980, 613628, 243571, 123684, 48197, 19696,
7830, 5308; 16551700, 8377890, 7159430, 2423150, 1001080, 521482, 223665,
82554, 39266, 14528, 5720, 3699; 10126100, 11796900, 5578130, 3575080,
1091650, 399091, 190292, 74539, 25356, 11305, 3993, 2491; 10552000,
9249540, 5358220, 3934970, 977988, 544329, 149467, 50908, 22577, 8286,
2677, 1790; 12499000, 7273070, 7691140, 2264030, 1325300, 363994, 123976,
54982, 20178, 6518, 25800, 1558; 10804900, 7809770, 6813200, 2072290,
1194120, 277982, 154676, 42472, 14466, 6416, 2354, 1269; 7508180, 7996000,
5753610, 3053760, 749010, 404048, 94032, 52322, 14367, 4893, 2170, 1226;
7357640, 5555400, 5892310, 3157060, 1416550, 326495, 176078, 40978, 22801,
6261, 2132, 1480; 8882310, 5446010, 4095710, 3025630, 1381460, 593723,
136818, 73786, 17172, 9555, 2624, 1514; 7306930, 6571630, 4008240,
1626650, 921627, 389671, 167415, 38579, 20806, 4842, 2694, 1167; 8057600,
5402470, 4829010, 1508230, 434058, 216488,    91482, 39304, 9057, 4885,
1137, 906; 5067850, 5950930, 3964520, 2099770, 425026, 98588, 49125,
20759, 8919, 2055, 1108, 464; 5100770, 3743210, 4369840, 1510300, 492937,
76764, 17786, 8862, 3745, 1609, 371, 284; 4851310, 3768190, 2751620,
1844580, 406186, 102961, 16016, 3711, 1849, 781, 336, 137; 9863940,
3583960, 2771730, 1197230, 527273, 95101, 24085, 3747, 868, 433, 183, 110;
6581610, 7279250, 2629800, 934009, 223835, 72705, 13096, 3317, 516, 120,
60, 40; 8149480, 4853550, 5329740, 723985, 124426, 20421, 6622, 1193, 302,
47, 11, 9; 5431190, 6013300, 3560890, 1922820, 115531, 10844, 1775, 576,
104, 26, 4, 2; 5366830, 4009420, 4416400, 1437290, 430531, 17521, 1642,
269, 87, 16, 4,   1; 5720080, 3966710, 2952760, 2215380, 472113, 103962,
4225, 396, 65, 21, 4, 1; 4394370, 4237510, 2925510, 2023300, 498939,
32119, 7017, 285, 27, 4, 1, 0; 6578780, 3255410, 3128770, 2035590, 519873,
71735, 4602, 1005, 41, 4, 1, 0; 5590490, 4873640, 2399370, 2110440,
238402, 29360, 4035, 259, 57, 2, 0, 0; 6099440, 4141520, 3598230, 1658530,
459731, 16295, 1991, 274, 18, 4, 0, 0; 6406360, 4518540, 3053150, 2418930,
207048, 24407, 861, 105, 14, 1, 0, 0];
original=original';



 Ftest=zeros(12,1000);
 stest=zeros(12,1000);
 Mage=zeros(12,1000);
 enhancetest=zeros(1,1000);
 Ctest=zeros(12,1000);
 area=zeros(1,1000);
 Mtest=zeros(1,1000);
 eigsreef=zeros(1,1000);
 dreef=zeros(1,1000);
 dparam=zeros(60,1000);
 dreefdparam=zeros(60,1000);
```

Appendix 2B Continued

```
    s0test=zeros(1,1000);
    f1test=zeros(1,1000);
    s1test=zeros(1,1000);
    f2test=zeros(1,1000);
    s2test=zeros(1,1000);
    f3test=zeros(1,1000);
    s3test=zeros(1,1000);
    f4test=zeros(1,1000);
    s4test=zeros(1,1000);
    f5test=zeros(1,1000);
    s5test=zeros(1,1000);
    f6test=zeros(1,1000);
    s6test=zeros(1,1000);
    f7test=zeros(1,1000);
    s7test=zeros(1,1000);
    f8test=zeros(1,1000);
    s8test=zeros(1,1000);
    f9test=zeros(1,1000);
    s9test=zeros(1,1000);
    f10test=zeros(1,1000);
    s10test=zeros(1,1000);
    f11test=zeros(1,1000);
    N0test=zeros(1,1000);
    N1test=zeros(1,1000);
    N2test=zeros(1,1000);
    N3test=zeros(1,1000);
    N4test=zeros(1,1000);
    N5test=zeros(1,1000);
    N6test=zeros(1,1000);
    N7test=zeros(1,1000);
    N8test=zeros(1,1000);
    N9test=zeros(1,1000);
    N10test=zeros(1,1000);
    N11test=zeros(1,1000);
    ftest=zeros(12,1000);
    Ntest=zeros(12,1000);

%Importing and naming the vectors possible age-specific parameters from
the press.m



%Creating vectors of randomly chosen parameters, taken from the vectors of
%possible age-specific parameters, above
s0pool=unifrnd(0.2756,0.7445,[1,1000]);
f1pool=unifrnd(0,0.8250,[1,1000] );
s1pool=unifrnd(0.3151,0.7489, [1,1000]);
f2pool=unifrnd(0,1.2763,[1,1000]);
s2pool=unifrnd(0.1966,0.5408,[1,1000]);
```

Appendix 2B Continued

```
f3pool=unifrnd(0,3.6834,[1,1000]);
s3pool=unifrnd(0.0833,0.4656,[1,1000]);
f4pool=unifrnd(0,5.3842,[1,1000]);
s4pool=unifrnd(0.0237,0.4395,[1,1000]);
f5pool=unifrnd(0,2.2906,[1,1000]);
s5pool=unifrnd(0.005,0.4124,[1,1000]);
f6pool=unifrnd(0,1.4028,[1,1000]);
s6pool=unifrnd(0.0014,0.3926,[1,1000]);
f7pool=unifrnd(0,0.3926,[1,1000]);
s7pool=unifrnd(.00029714,0.3745,[1,1000]);
f8pool=unifrnd(0,0.2429,[1,1000]);
s8pool=unifrnd(.000058242,0.3606,[1,1000]);
f9pool=unifrnd(0,0.1141,[1,1000]);
s9pool=unifrnd(.000012501,.4974,[1,1000]);
f10pool=unifrnd(0,0.0410,[1,1000]);
s10pool=unifrnd(0,0.65201,[1,1000]);
f11pool=unifrnd(0,0.0436,[1,1000]);

%Creating a vector of 20 randomlly chosen natural mortality, from three
possible values (SEDAR 2002), weighted based on
%2002 Stock Assessment (SEDAR 2002).

Mpool=unifrnd(0.2,0.4,[1,1000]);




%Creating a distribution of possible reef enhancement
enhancepool=unifrnd(0.00001,0.2415,[1,1000]);

N0pool=(unifrnd(0,1.7833e07,[1,1000]));
N1pool=(unifrnd(0,1.3152e07,[1,1000]));
N2pool=(unifrnd(0,9.7533e06,[1,1000]));
N3pool=(unifrnd(0,7.433e06,[1,1000]));
N4pool=(unifrnd(0,6.2316e05,[1,1000]));
N5pool=(unifrnd(0,6.8065e05,[1,1000]));
N6pool=(unifrnd(0,2.5941e03,[1,1000]));
N7pool=(unifrnd(0,289.4301,[1,1000]));
N8pool=(unifrnd(0,41.3643,[1,1000]));
N9pool=(unifrnd(0,2.9589,[1,1000]));
N10pool=(repmat(1,1,1000));
N11pool=(repmat(0,1,1000));

run=1;
while run ~=1000
```

Appendix 2B Continued

```
s0test(:,run)=s0pool(:,run);
    f1test(:,run)=f1pool(:,run);
    s1test(:,run)=s1pool(:,run);
    f2test(:,run)=f2pool(:,run);
    s2test(:,run)=s2pool(:,run);
    f3test(:,run)=f3pool(:,run);
    s3test(:,run)=s3pool(:,run);
    f4test(:,run)=f4pool(:,run);
    s4test(:,run)=s4pool(:,run);
    f5test(:,run)=f5pool(:,run);
    s5test(:,run)=s5pool(:,run);
    f6test(:,run)=f6pool(:,run);
    s6test(:,run)=s6pool(:,run);
    f7test(:,run)=f7pool(:,run);
    s7test(:,run)=s7pool(:,run);
    f8test(:,run)=f8pool(:,run);
    s8test(:,run)=s8pool(:,run);
    f9test(:,run)=f9pool(:,run);
    s9test(:,run)=s9pool(:,run);
    f10test(:,run)=f10pool(:,run);
    s10test(:,run)=s10pool(:,run);
    f11test(:,run)=f11pool(:,run);

    N0test(:,run)=N0pool(:,run);
    N1test(:,run)=N1pool(:,run);
    N2test(:,run)=N2pool(:,run);
    N3test(:,run)=N3pool(:,run);
    N4test(:,run)=N4pool(:,run);
    N5test(:,run)=N5pool(:,run);
    N6test(:,run)=N6pool(:,run);
    N7test(:,run)=N7pool(:,run);
    N8test(:,run)=N8pool(:,run);
    N9test(:,run)=N9pool(:,run);
    N10test(:,run)=N10pool(:,run);
    N11test(:,run)=N11pool(:,run);
    Ntest(:,run)=[N0test(:,run); N1test(:,run); N2test(:,run);
N3test(:,run); N4test(:,run); N5test(:,run); N6test(:,run); N7test(:,run);
N8test(:,run); N9test(:,run); N10test(:,run); N11test(:,run)];



    enhancetest(:,run)=enhancepool(:,run);
```

Appendix 2B Continued

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%5
    %%%%%STEP TWO.  DETERMINING THE CURRENT CATCH OF THE POPULATION (IN
2004)
  %Reforming the survival and fertility vectors to make future
    %calculations easier
    stest(:,run)=[s0test(1,run),s1test(1,run), s2test(1,run),
s3test(1,run), s4test(1,run), s5test(1,run), s6test(1,run), s7test(1,run),
s8test(1,run), s9test(1,run), s10test(1,run), 0];

    %Taking the appropriate the natural mortality, and creating a vector
of
    %constnat natural mortality across all age classes
    Mtest(:,run)=Mpool(:,run);
    Mage(:,run)=repmat(Mtest(:,run),12,1);

   %Creating the vector of fishing mortality, from surival and natural
   %mortality.  F=fishing mortality.
    Ftest(:,run)=-Mage(:,run)-log(stest(:,run));

Ftest((Ftest<0))=0;
Ftest(12,run)=0;
Ftest(stest<0)=0;




  %Creating the vector of age-specific catch.  C=catch
      Ctest(:,run)=(Ntest(:,run).*Ftest(:,run)).*(1-exp(-
(Ftest(:,run)+Mage(:,run)))./(Ftest(:,run)+Mage(:,run));
      %Creating a matrix of age-specific catch, constant over a 30 year
model
%period







%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%5
    %%%%%STEP TWO.  DETERMINING THE CURRENT CATCH OF THE POPULATION (IN
2004)

    %Reforming the survival and fertility vectors to make future
```

Appendix 2B Continued

```
    ftest(:,run)=[0; f1test(1,run); f2test(1,run); f3test(1,run);
f4test(1,run); f5test(1,run); f6test(1,run); f7test(1,run); f8test(1,run);
f9test(1,run); f10test(1,run); f11test(1,run)];
    %creating the transition matrix for the population parameters pulled
if
    %fishing mortality =0.  If the eigenvalue of this matrix is <1, the
    %popultion is not biologically realistic, and another set of
    %population parameters is chosen
    atest=zeros(12,12);
    atest(1,:)=ftest(:,run);
    for ii=1:11
        atest(ii+1,ii)=exp(-(Mtest(:,run)));
    end
   opts.disp=0;
   eigstest=max(real(eigs(atest,4,'LM',opts)));

    atest2=zeros(12,12);
    atest2(1,:)=ftest(:,run);
    for gg=1:11
    atest2(gg+1,gg)=stest(gg,run);
    end
    opts.disp=0;
    eigstest2=max(real(eigs(atest2,4,'LM',opts)));
if eigstest<1
elseif eigstest2>=1
  area(:,run)=0;
else

S=stest(:,run);
if S(1:11,:)==0
    S(1:11,:)=0.0001;
end

F=Ftest(:,run);
M=Mage(:,run);
C=Ctest(:,run);
N=Ntest(:,run);
f=ftest(:,run);
enhance=enhancetest(:,1);



min_reef_area=1;
max_reef_area=100000000000000;
desired_eigenvalue=1;

iterations=1;
eigsreef=-999; %unimportant starting value so while loop will work
```

Appendix 2B Continued

```
area_guess=max_reef_area-((max_reef_area-min_reef_area)/(2^iterations));

while (round(eigsreef*10000)/10000) ~= desired_eigenvalue
if area_guess<1.9999
break
else



iterations=iterations+1;
Reef=area_guess;
area(:,run)=area_guess;



%Creating the vector of age-specific abundance in the presence of the reef
(Nreef).  The reef
%enhancement is added to the first age group, and the age 0 population is
%moved through the age-classes.  Survival*Abundance in age class
%t=Abundance in age class t+1

Nreef=zeros(12,1);
Nreef(1,1)=N(1,1)+(Reef*enhance);
for e=2:12;
    Nreef(e,:)=Nreef((e-1),:)*S((e-1),:);
end

%Catch is held constant with increasing reef area, since the objective of
%the study is to determine the reef area neccesary to restore the
%population without reducing catch.  In order to determine fishing
%mortality in the presence of the reef (Freef), the Freef wich minimizes
the squared difference
%between catch without reef and catch with reef is determined using in an
%interative optimization program called patternsearch.  Patternsearch is
%part of MATLAB's Genetic Algorithm and Direct Search Toolbox.
%(http://www.mathworks.com/access/helpdesk/help/pdf_doc/gads/gads_tb.pdf)

%Objfun is the sum of the difference squared, over all age classes, and is
the scalar value which will be minimized.
objfun=@(Freef) sum((C-(Nreef.*Freef.*(1-exp(-
(Freef+M))./(Freef+M))).^2);



% lb=[0;0;0;0;0;0;0;0;0;0;0;0];
% ub=[1;1;1;1;1;1;1;1;1;1;1;1];
x0=F;
```

Appendix 2B Continued

```
%The function patternsearch finds Freef within the upper and lower bounds,
%starting at F such that objfun is minimized
 lb=repmat(0,12,1);
 ub=repmat(5,12,1);
  %[Freef,fval,exitflag
]=patternsearch(objfun,x0,[],[],[],[],lb,ub,[],psoptimset('Display','off')
)
[Freef,fval,exitflag]=patternsearch(objfun,x0,[],[],[],[],lb,ub,[],psoptim
set('Display','off','completepoll', 'on'));

%Creating the vector of age-specific survival in the presence of the reef,
%based on M and Freef (fishing mortality in the presence of the reef)

Sreef=exp(-(Freef+M));



if (S(11,1)<0.001 && Sreef(11,1)>exp(-(M(1,1))));
        Sreef(11,1)=0;
end

Sreef(12,1)=0;



%Determining the eigenvalue of the population in the presence of the reef
areef=zeros(12,12);
areef(1,:)=f;
for s=1:11
    areef(s+1,s)=Sreef(s,1);
end
opts.disp=0;
eigsreef=max(real(eigs(areef,4,'LM',opts)));

%if the eigenvalue is <0.999999999, the reef area is increased by 1,000
%meters squared and the process is repeated.  If it is >0.999999999, the
%program stops.





if eigsreef < desired_eigenvalue
   area_guess = area_guess+((max_reef_area-min_reef_area)/(2^iterations));
else
   area_guess = area_guess-((max_reef_area-min_reef_area)/(2^iterations));

end
```

Appendix 2B Continued

```
end
end
end
% run=run+1
if area(:,run)~=1
  run=run+1;
end



% end



end
```