# A Spatiotemporal Bioeconomic Model For Marine Reserve Design

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**Abstract:** A spatiotemporal bioeconomic model is developed for economic analysis of marine reserves. The model has been designed to reflect the dynamics of biological fish stocks, fishing behavior and economic aspects among a number of spatial cells. The model features (1) multiple age cohorts of fish stocks, (2) multiple fish species, (3) age, depth and density dependent migration between cells, (4) density dependent natural mortality, (5) depth dependent fishing costs, and (6) spatially heterogeneous spawning behavior. For the purposes of illustration, only 16 cells in the form of a 4 by 4 array are considered in this study. Results are presented on the optimal distribution of fishing effort over cells for each reserve configuration and on optimal reserve designs under several criteria. Opportunity costs of imposing marine reserves are also discussed. Furthermore, some tests of the sensitivity of the results to the model's parameters (e.g. natural mortality rates, migration rates and fishing costs) are performed.

***Keywords:*** *marine reserve design, opportunity cost, spatiotemporal bioeconomic model, and fish migration*

## 1. INTRODUCTION

Marine reserves have attracted much attention in recent years (e.g. Polacheck (1990), DeMartini (1993), Holland and Brazee (1996), Holland (2000), Tuck and Possingham (2000), Pezzey et al. (2000), Sanchirico and Wilen (2000) and Lawson and Gooday (2000)). One of the reasons is that conventional management measures such as quotas and gear restrictions have often failed to prevent depletion or collapse of many fish stocks. The difficulty and complexity of setting and implementing such conventional measures is another reason for considering marine reserves. Difficulties due to, for example, the large number of fishers, the variety of fishing technologies and the number of potential landing sites, also make conventional methods more expensive to use (e.g. Roberts and Polunin (1991)).

The benefits of adopting marine reserves have been discussed in several published papers (e.g. Holland and Brazee (1996)). Generally, the benefits consist of the contributions that reserves make to marine resource management objectives such as protection of ecosystems, promotion of sustainable commercial fisheries and development of recreational activities. Although marine reserves in the first instance would lead to smaller commercial harvests, this cost may be reduced over time through the provision of natural hatcheries and nurseries, and a reduction in the risk of fishery collapse.

In this study a spatiotemporal bioeconomic model is proposed to simulate the effects on net fishing revenue and fish stocks of alternative marine reserve configurations. The effects reflect efficient adjustment in fishing effort following reservation. No attempt is made to assess the non-fishery related costs and benefits of reserves. In contrast to other published models (e.g. Holland and Brazee (1996)), this model is age-structured and has multiple fish species; fish migration depends upon age, depth, and population density; and natural mortality is density dependent. Sixteen spatial cells are considered in the model. The layout and cell labels are shown in Figure 1. Cells in the same column have the same depth.

| | | | |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 |
| 13 | 14 | 15 | 16 |

Inshore(low depth) → Offshore(high depth)

**Figure 1.** Layout of fishery cells.

## 2. A SPATIOTEMPORAL BIOECONOMIC MODEL

Although the specification reflects features of real fisheries, the current model is implemented for a hypothetical fishery. Multiple age cohorts, multiple species, stock-recruitment relationships, and density dependent mortality and migration are all represented in the model. In contrast to, e.g. Holland and Brazee (1996), fishing effort in each cell is not assumed fixed but is determined by maximization of the net present value of the fishery subject to marine reserve constraints.

Thus, the results presented here are for an efficiently managed fishery for any set of reserves. The model contains some spatial heterogeneity among cells with some model variables depending on depth characteristics. For example, offshore or inshore cells with high or low depths have low or high migrations, deeper cells incur higher fishing costs; and middle depth cells have highest spawning rates.

The model specification is as follows:

First, a Beverton and Holt (1957) stock-recruitment relationship is used to estimate the age 1 cohort (i.e. recruits). It is assumed that recruits grow up in a common nursery ground of the fishery before entering into each cell of the fishery. The distribution of recruitment into each cell is assumed known. It is also assumed males and females are equal in number in any age cohort.

$$x_i(s,1,t+1) = r(s,t+1)\theta_i(s), \tag{1}$$

$$S(s,t) = 0.5\sum_i \sum_a x_i(s,a,t)w(s,a)\varsigma_i(s,a) \tag{2}$$

$$r(s,t) = a_r(s)S(s,t-1)/[1+b_r(s)S(s,t-1)] \tag{3}$$

where

- $x_i(s,a,t)$ is the number of fish of age $a$ and species $s$ in cell $i$ at the beginning of period $t$; age 1 represents new recruits;
- $S(s,t)$ is the spawning stock biomass of species $s$ in period $t$ for the whole fishery;
- $r(s,t)$ is the recruitment of species $s$ at the beginning of period $t$, which is estimated from the Beverton and Holt (1957) stock-recruitment curve; and
- $\theta_i(s)$, $w(s,a)$, $\varsigma_i(s,a)$, $a_r(s)$ and $b_r(s)$ are model parameters (see Table 1). Note that the spawning rate, $\varsigma_i(s,a)$, varies across cells.

In each period and in each cell, the number of fishes of ages older than one is estimated from fishes one year younger by considering migrations between cells and natural and fishing mortalities during the previous period. Migrations between cells are assumed to depend upon age, depth and population density. It is also assumed natural mortality depends upon density.

$$\begin{aligned} x_i(s,a+1,t+1) = [&x_i(s,a,t)(1-eg_i(s,a,t)) \\ &+ig_i(s,a,t)]e^{-Z_i(s,t)}, \quad (a<A) \end{aligned} \tag{4}$$

$$\begin{aligned} x_i(s,A,t+1) = [&x_i(s,A-1,t)(1-eg_i(s,A-1,t)) \\ &+ig_i(s,A-1,t)+x_i(s,A,t)(1-eg_i(s,A,t)) \\ &+ig_i(s,A,t)]e^{-Z_i(s,t)}, \qquad (a=A) \end{aligned} \tag{5}$$

$$d_i(t) = \sum_{s,a} w(s,a)x_i(s,a,t)/\sigma_i \tag{6}$$

$$rd_{i,k}(t) = d_k(t)/d_i(t) \tag{7}$$

$$\begin{aligned} d_i^*(t) = \sum_{s,a} \{&w(s,a)[x_i(s,a,t)(1-eg_i(s,a,t)) \\ &+ig_i(s,a,t)]\}/\sigma_i \end{aligned} \tag{8}$$

$$m_i(s,t) = a_m(s)/[b_m(s)+e^{c_m(s)d_i^*(t)}] - a_m(s)/(b_m(s)+1) \tag{9}$$

$$g_{i,k}(s,a,t) = \begin{cases} 0, & k \neq i-1, i+1, i-4, i+4; \\ gd_i(s)ga(s,a)/[a_d + b_d rd_{i,k}(t)], & \\ \text{otherwise} & \end{cases} \tag{10}$$

$$eg_i(s,a,t) = \sum_{k(k\neq i)} g_{i,k}(s,a,t) \tag{11}$$

$$ig_i(s,a,t) = \sum_{k(k\neq i)} x_k(s,a,t)g_{k,i}(s,a,t) \tag{12}$$

$$f_i(s,t) = q(s,s)E_i(s,t)\eta_i + \sum_{s'(s'\neq s)} q(s,s')E_i(s',t)\eta_i \tag{13}$$

$$Z_i(s,t) = m_i(s,t) + f_i(s,t) \tag{14}$$

where

- $A$ is the oldest age considered;
- $g_{i,k}(s,a,t)$ is the migrating proportion from cell $i$ to cell $k$, which depends on depth, age and density (it is assumed that migration movements only occur between neighboring cells during each period);
- $eg_i(s,a,t)$ is the emigrating proportion from cell $i$;
- $ig_i(s,a,t)$ is the total number of immigrants into cell $i$;
- $d_i(t)$ is the population density in cell $i$;
- $d_i^*(t)$ is the population density in cell $i$ after migration at time $t$, which is used to estimate the density dependent natural mortality during time $t$;
- $rd_{i,k}(t)$ is the relative density between the cells $i$ and $k$ at the beginning of time $t$;
- $m_i(s,t)$ is the natural mortality and depends upon population density according to a simple function asymptotically approaching a given ceiling;
- $f_i(s,t)$ is the fishing mortality which is linearly dependent on fishing effort $E_i(s,t)$ and catchability $q(s,s')$;
- $\eta_i$ is a 0-1 variable representing whether cell $i$ is open to fishing or not (0: reserved, 1: fished);

- $Z_i(s,t)$ is the total mortality, and
- $\sigma_i$, $gd_i(s)$, $ga(s,a)$, $a_d$, $b_d$, $a_m$, $b_m$, $c_m$ and $q(s,s')$ are parameters (see Table 1).

Harvest is estimated as the proportion of deaths resulting from fishing mortality out of the total deaths from total mortality. Revenue is the product of price $p(s,a)$ and harvest weight summed over all ages, species and cells. Cost is the product of fishing effort and the cost per unit effort $c_i(s)$ summed over all species and cells.

$$\begin{aligned} h_i(s,a,t) = w(s,a)[x_i(s,a,t)(1-eg(s,a,t)) \\ + ig_i(s,a,t)](1-e^{-Z_i(s,t)})f_i(s,t)/Z_i(s,t) \end{aligned} \quad (15)$$

$$TR(t) = \sum_{s,i,a} p(s,a)h_i(s,a,t) \quad (16)$$

$$TC(t) = \sum_{s,i} \eta_i E_i(s,t)c_i(s) \quad (17)$$

where

- $h_i(s,a,t)$ is the harvest weight by cell, species and age;
- $TR(t)$ is the total revenue;
- $TC(t)$ is the total cost;
- $p(s,a)$ and $c_i(s)$ are parameters (Table 1).

*Profit maximization*

The objective is to maximize the sum of discounted net returns $V$

$$V = \sum_{t=1}^{\infty} (TR(t) - TC(t))(1+\tau)^{1-t}, \quad (18)$$

with respect to fishing efforts $E_i(s,t)$ and reserve configuration $\eta_i$, subject to all equations specified above as well as relevant end conditions; $\tau$ is the discount rate (see Table 1).

**Table 1.** Model parameters and their values

| Parameters | Descriptions | Values |
|---|---|---|
| $i$ | Cell index | 1, 2, …, 16 |
| $s$ | Species index | 1, 2 |
| $a$ | Age index (in years) | 1, 2, 3 ($A$ = 3) |
| $t$ | Time index (in years) | 1, 2, 3, … |
| $\theta_i(s)$ | Proportion of total recruitments in cell $i$ | $\theta_i(1) = \theta_i(2)$ = 0.0875, 0.075, 0.05, 0.0375, 0.0875, 0.075, 0.05, 0.0375, 0.0875, 0.075, 0.05, 0.0375, 0.0875, 0.075, 0.05, 0.0375 |
| $w(s,a)$ | Fish weight (kg) | $w(1,a)$ = 1, 1.5, 2; $w(2,a)$ = 0.8, 1.2, 1.5 |
| $\varsigma_i(s,a)$ | Proportion of spawners | 0 if $a$ = 1; 0.7 if mod ($i$, 4) $\leq$ 1 & $a$ > 1; 1 if mod ($i$, 4) > 1 & $a$ > 1 |
| $a_r(s), b_r(s)$ | Stock-recruitment parameters | $a_r(1)$ = 2, $a_r(2)$ = 3, $b_r(s)$ = 0.00001 for all $s$ |
| $\sigma_i$ | Size of cell $i$ | 1 for all $I$ |
| $gd_i(s)$ | Depth dependent migration rate | $gd_i(1) = gd_i(2)$ = 0.8, 0.5, 0.3. 0.1, 0.8, 0.5, 0.3, 0.1, 0.8, 0.5, 0.3, 0.1, 0.8, 0.5, 0.3, 0.1 |
| $ga(s,a)$ | Age dependent migration rate | $ga(1,a) = ga(2,a)$ = 0.9, 0.5, 0.1 |
| $a_d, b_d$ | Density dependent migration parameters | $a_d = 2$, $b_d = 10$ |
| $a_m, b_m, c_m$ | Density dependent mortality parameters | $a_m = 1351.14$, $b_m = 39.65, c_m = -0.0000457$ |
| $q(s,s')$ | Own, cross catchability | $q(s,s)$ = 0.005; $q(s,s')$ = 0.0005 ($s \neq s'$) |
| $p(s,a)$ | Prices ($/kg) | $p(1,a)$ = 10, 12, 14; $p(2,a)$ = 8, 10, 12 |
| $c_i(s)$ | Fishing cost per unit of effort ($) | $c_i(1) = c_i(2)+1$; and $c_i(2)$ = 9, 10, 11, 12, 9, 10, 11, 12, 9, 10, 11, 12, 9, 10, 11, 12 |
| $\tau$ | Discount rate | 0.07 |

## 3. SIMULATIONS AND RESULTS

In this section, the results of simulations with the model are given. The results are obtained as follows. For each reserve configuration, the optimal steady state fishing effort is determined by maximizing the steady state net return from the fishery. This yields, for each reserve configuration, the steady state fish stocks and net returns (Section 3.1). Simulations are not performed over time in this study for computational reasons. Computing fish stocks and net returns by running the model over a long time is problematic due to the large number of decision variables in the model. Unless a sufficiently long time horizon is chosen, the optimization will not adequately account for the value of remaining fish stocks. A steady state approach avoids this terminal value problem. Having obtained net returns and fish stocks by species, age and cell, for all possible reserve configurations, Section 3.2 discusses criteria for making marine reserve decisions and the corresponding optimal reserve designs. Section 3.3 reports on the sensitivity of the optimal reserve design to model parameters.

### 3.1. Steady state returns and fish stocks for all possible reserve configurations

In steady state, there is no change over time in any state or co-state variable of the model. Conditions or equations on the co-state variables are obtained from the first order conditions of the optimization problem with objective function (18). To save space the co-state equations are not listed here. After dropping the time index $t$ in all equations including the co-state equations, the steady state can be obtained by solving the complete system.

To determine the effects of marine reserves, up to three cells are considered for reservation. If all cells are assumed to be of equal size, reserving one, two or three cells means a total of 6, 13 or 19% of the fishery area is reserved, respectively.

For any reserve configuration, the steady state net return and fish stock numbers are derived with the model. The number of possible configurations depends on the number of cells considered for closure. For reservation of one cell, there are 16 possible reserve configurations; for reservation of two cells 120 configurations and for three cells 560 configurations.

### 3.2. Optimal reserve design under various criteria

Having obtained the steady state net returns and fish stock numbers for all possible reserve configurations, several management criteria are formulated and the corresponding optimal reserve designs are discussed. The single variable criteria used are minimal opportunity costs (i.e. minimal reduction in net returns compared with the case of no reservation), and maximal increase in the spawning stock biomass for each species. In reality, marine resource managers may need to consider a wider ranging criterion that could be represented by a preference function defined over combinations of net returns and fish stocks for the various species. However, the process of eliciting such a function would be difficult and is outside the scope of the this paper.

The spawning stock biomass (SSB) is used as a measure of fish stocks. This is a conventional measure to summarize the stock status of a fishery. As the model is for a multi-species fishery, there is an SSB for each species. In our hypothetic fishery, two species are considered, both of them are the target species, and there is no prey-predator relationship between them.

The optimal reserve design under a chosen criterion is the reserve configuration that optimizes the criterion. For our problem with a maximum number of reserve configurations of 560 in the case of reservation of three cells, an exhaustive search is carried out. For larger problems, search techniques such as simulated annealing (e.g., see Kirkpatrick et al. (1983) and Leslie et al. (2002)) could be used.

The optimal reserve designs under several single variable criteria (i.e. minimal opportunity costs and maximal SSB) are shown in Table 2, where 'Differences from base case values' are the values at the optimal reserve design less the corresponding values at the base case without a reserve. SSB1 and SSB2 represent the spawning stock biomass for species 1 and species 2, respectively. The criterion of maximal spawning stock biomass is applied to each species separately, however, they give the same optimal reserve design. For the hypothetical fishery considered, it turns out that the stocks of the two species respond in rather similar ways to harvesting and reservation. This leads to the same optimal reserve design under the SSB criterion for each of the species.

Considering net returns, there is an opportunity cost (see $\Delta NR$ ) associated with the imposition of a reserve under whatever criterion. However, this opportunity cost should be seen against increases in the fish stocks (i.e. SSB). The enhanced fish stocks may well be regarded as more than compensating for the loss in net returns upon imposition of a marine reserve, as they contribute to the biological and economic sustainability of the fishery by lowering the risk of stock collapse.

In addition to the enhancement of fish stocks, a marine reserve may also provide benefits to non-target species. These benefits are not included in the model.

Table 3 contains fishing effort in each cell for the base case of no reserves and two cases of reservation of three cells: 3, 7 and 15; and 1, 5 and 9. Reservation of cells 3, 7 and 15 is the optimal reserve design under the criterion of minimal opportunity costs (Table 2). Cells 1, 5 and 9 are chosen from the lowest depth cells (see Figure 1) and have the lowest fishing costs. Reservation of cells 1, 5 and 9 is chosen in order to compare its corresponding allocation of fishing effort with that of the other two cases.

In all cells that are fished, fishing effort is higher in the reserve case than in the base case. The efforts expended in the reserved cells in the base case are redistributed to the other cells. Proportional increases in fishing efforts are greatest in cells adjacent to the reserved cells (e.g. cells 2, 6 and 14). It is also interesting to note that the total fishing effort when cells 3, 7 and 15 are reserved is slightly higher than in the base case. This can be explained by a shift of effort to low depth cells where fishing costs are lower induced by the reservation of high depth cells associated with higher fishing costs. When low depth cells are reserved, e.g. cells 1, 5 and 13, effort is shifted to high depth cells with higher fishing costs resulting in lower total fishing effort than in the base case.

**Table 2.** Optimal reserve designs with different criteria.

| Reserving | Optimal cell(s) for a reserve | Values at optimal reserve | | | Differences from base case values | | |
|---|---|---|---|---|---|---|---|
| | NR Criterion | NR | SSB1 | SSB2 | ΔNR | ΔSSB1 | ΔSSB2 |
| One cell | 7 or 11 | 614191 | 35931 | 45067 | -4362 | 176 | 380 |
| Two cells | 7, 15 or 3, 11 | 609099 | 36136 | 45523 | -9454 | 381 | 836 |
| Three cells | 3, 7, 15 or 3,11,15 | 602846 | 36387 | 46094 | -15707 | 632 | 1407 |
| | SSB Criterion | NR | SSB1 | SSB2 | ΔNR | ΔSSB1 | ΔSSB2 |
| One cell | 2 or 14 | 611188 | 36072 | 45257 | -7365 | 317 | 570 |
| Two cells | 2, 6 or 10, 14 | 602137 | 36465 | 45980 | -16416 | 710 | 1293 |
| Three cells | 2, 6, 10 or 6, 10, 14 | 591401 | 36934 | 46870 | -27152 | 1179 | 2183 |

**Table 3.** Optimal distributions of fishing effort in each cell with reserve and without reserve (base case).

| Cells | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Base case | 177 | 80 | 55 | 120 | 158 | 80 | 55 | 120 | 158 | 80 | 55 | 120 | 158 | 80 | 55 | 101 | 1652 |
| 3,7,15 | 191 | 99 | 0 | 133 | 172 | 99 | 0 | 133 | 172 | 95 | 72 | 131 | 172 | 99 | 0 | 113 | 1681 |
| 1,5,13 | 0 | 123 | 81 | 155 | 0 | 121 | 81 | 140 | 224 | 109 | 81 | 155 | 0 | 121 | 81 | 120 | 1592 |

### 3.3. Sensitivity with respect to model parameters

To see how the reserve design depends on model parameters, some sensitivity tests are conducted below. These focus on natural mortality rates, migration rates, and fishing costs.

Sensitivity tests were conducted with respect to three key parameters of the model: the parameter $b_d$ for the density dependent migration rates, the parameter $c_m$ for the density dependent natural mortality rates, and the parameter $c_i(s)$ for the fishing costs. The analysis was limited to two cell reserves.

(i) Decrease $b_d$ from 10 in the base case to 6. This increases the migration rates (see (10)). It is found that the optimal cells for a reserve under both the NR and SSB criteria are the same as in the base case. However, the opportunity cost of imposing the optimal reserve is slightly reduced, and the SSBs are higher accordingly.

(ii) Decrease $c_m$ from –0.0000457 in the base case to –0.0000914. This doubling significantly increases the mortality rates (see (9)). It is found that the optimal cells for a reserve under each of the criteria are also the same as in the base case. However, stock levels and net revenues are significantly reduced due to the higher natural mortality.

(iii) Increase the fishing costs $c_i(s)$ from (9, 10, 11, 12) to (9, 11, 13, 15), where the four numbers in the bracket represent the fishing costs of species 2 for the cells in the four columns (see Figure 1). Costs for cells in the same column are the same. Costs for the first species are one unit greater than the costs for the second species (see Table 1). This increase in fishing costs does not alter the optimal reserve design in the base case under all criteria. However, the opportunity cost and the SSBs under the optimal reserve are both increased due to the higher fishing costs, compared with the base case.

## 4. CONCLUSIONS AND DISCUSSION

A spatiotemporal bioeconomic model is formulated for the design of marine reserves. The model reflects features of a real fishery, including multiple age cohorts, multiple species, density dependent migrations and natural mortality, and spatially heterogeneous fishing costs and spawning behavior. These features are essential for exploring the importance of spatial interdependence of fish species for marine reserve designs. Some model results for optimal reserve design are shown for a hypothetical fishery. The opportunity costs, fish stocks and efficient effort levels under a marine reserve were discussed and showed that spatial interactions are important for the optimal design and its impact.

The finding that the optimal reserve design is not sensitive to some key model parameters may have some implications in practical applications, noting that the key parameters (e.g. parameters for the density dependent migrations and natural mortalities) are usually difficult to measure in a real fishery.

The approach taken to the optimal reserve design presented in this paper is just one of a number of methods that could be considered. Further work could include the design of marine reserves under a range of fishery management regimes such as open access. Application of the model to real fisheries is being considered.

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