

Marine Reserves for Fisheries Management

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Abstract *Conventional methods of regulating commercial fisheries restrict catch by limiting either the quantity or efficiency of fishing effort, or by putting direct limits on catch. These regulatory practices are neither feasible nor desirable for many fisheries, and have failed to conserve fishery stocks in other fisheries. Marine reserves may be an effective alternative management strategy for some fisheries. Here we develop a dynamic model of marine reserves applicable to inshore fisheries. In contrast to previous models of reserves, the model is fully dynamic and provides information on both equilibrium conditions and the path to equilibrium. A simulation model based on red snapper data from the Gulf of Mexico is presented. The simulation results suggest that marine reserves can sustain or increase yields for moderate to heavily fished fisheries but will probably not improve yields for lightly fished fisheries.*

Key words Closed areas, inshore fisheries, marine protected areas, marine reserves, reef fisheries.

Conventional methods of regulating commercial fisheries including limited licenses, catch quotas, taxes on catch or effort, gear restrictions, and closed seasons restrict catch by limiting either the quantity or efficiency of fishing effort, or by putting direct limits on total catch (Cunningham 1983). Although widely applied, conventional methods have often failed to prevent depletion or collapse of many fish stocks. In some fisheries, due to the large number of fishers, numerous landing sites, variety of fishing technologies, or complex interspecific interactions, these methods of regulation are difficult and/or expensive to use (for example, see Roberts and Polunin 1991; Holland, *et al.* 1995.).

Several fisheries scientists (Bohnsack 1990; Carr and Reed 1992; Davis 1989; Roberts and Polunin 1991, 1993; Sadovy 1992; Rowley 1994) have suggested that for some fisheries, closing part of the fishery through the creation of marine reserves may sustain or increase harvests. Marine reserves act as a natural hatchery and nursery in which reproduction and growth are not impeded. The populations that develop in reserves supplement surrounding fisheries through export of larvae and adult fish. Marine reserves may also reduce the risk of fishery collapse by maintaining a more diverse age structure and genetic base.¹ Reserves will likely be most effective for sustaining or increasing harvests in inshore fisheries² in which adults are

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¹ Trippel (1995) notes that the reproductive capability and resiliency to environmental fluctuations of heavily fished populations may be reduced as the average age and average age of maturity is reduced.

² Inshore fisheries are shallow water marine fisheries which are close to shore. Inshore fisheries include mangrove swamps, reefs, estuaries, and lagoons.

non-migratory residents. However reserves may be useful for other fisheries as well.³

Marine reserves differ from conventional regulatory methods in that they close a portion of the fishery, and do not directly attempt to reduce harvests, fishing effort, or the efficiency of fishing effort. Although marine reserves may increase fishery production and may reduce the probability of a collapse of the fishery, they are not generally first-best strategies that will lead to economically efficient use of the resource. Marine reserves may provide a stand-alone management strategy when first-best methods are unable to directly control effort or catch due to political or technical unfeasibility or expense. They may also be a valuable component of a multifaceted management policy.

Our purpose is to present a simple economic analysis of marine reserves as a tool of fishery management. This analysis is intended to be a first step in addressing an important omission in the literature. Previous models of marine reserves have been yield per recruit analyses (Polacheck 1990; DeMartini 1993). These analyses are biologically oriented, only generate information about steady-states, and omit important economic variables such as price, interest rates, and minimum constraints on fishery production. Empirical studies of marine reserves have focused on the conservation benefits of habitat and organisms within the boundaries of reserves (Bohnsack 1982; Clark, *et al.* 1989; Causey and Bohnsack 1989; Roberts and Polunin).⁴ Rowley (1994) has compiled an extensive summary of evidence regarding the ability of reserves to supplement surrounding fisheries, but finds that further research, including simulation, will be required before firm conclusions can be drawn.

We begin with a dynamic model of a fishery in which a marine reserve is introduced. In contrast to most previous economic models of fisheries, total effort is assumed to be fixed. This implies that effort will not be reduced with the introduction of a reserve and that it is possible to limit future increases in effort if rents occur from the introduction of a reserve.⁵ Unlike previous models of marine reserves, the optimal reserve size is determined by maximizing the present value of harvests over a planning horizon, rather than by maximizing sustainable yields. Two other key differences between this model and previous models of marine reserves are the inclusion of multiple age classes and a stock recruitment relationship.⁶ With these inclusions, the effects of changing population size and age structure on recruitment and harvest over time can be investigated. Unlike previous models, the time paths of harvests and fish stocks prior to reaching a steady-state are determined. The time paths of harvests and stocks are important because the full impact of the reserve may not be realized for several years. Consideration of the time paths also demonstrates a new and potentially important result; that is, the optimal reserve size varies inversely with the discount rate.

Although the dynamic model is a simplified description of the introduction of a

³ Extensive, long term area closures will be used in the groundfish fisheries off the coasts of Atlantic Canada and New England to promote the recovery of depleted stocks (NEFMC 1996).

⁴ One exception is Alcalá (1988). He noted the drop in harvests for a small island fishery when a small reserve was eliminated. However, the results are not conclusive. The drop in harvests could have been due to natural fluctuations in recruitment.

⁵ We assume fishing effort is fixed for simplicity. Known, exogenous shifts in fishing effort are straightforward to include. It is reasonable to assume that fishing effort is fixed, when total fishing effort is regulated by other methods, or in a subsistence fishery for which the surrounding population is constant.

⁶ Recruitment refers to the number of juvenile fish that enter the fishery (*i.e.*, grow to fishable size). A stock recruitment relationship refers to recruitment as a function of the adult population of the fishery. Polacheck (1990) underscores the need to incorporate a stock recruitment relationship.

reserve due to the complexities of modeling age structure, unambiguous qualitative results are scarce. To more fully investigate introducing reserves and to begin examining the potential quantitative impacts from introducing reserves, we present a numerical simulation based on red snapper data from the Gulf of Mexico. Red snapper is a species common in many inshore fisheries, and shares several characteristics with other target species commonly found in inshore fisheries. In the simulation, optimal reserve size is determined under varying biological conditions and effort levels. The simulation results suggest that marine reserves will sustain or increase harvests in heavily fished, inshore fisheries. This contrasts with previous studies that do not incorporate a stock recruitment relationship. In these previous studies that did not model a stock-recruitment relationship (DeMartini 1993; Polacheck 1990) marine reserves generally do not sustain or increase harvests.⁷ The sensitivity analysis also illustrates the importance of key biological assumptions on results.

Model of a Marine Reserve

In this section we develop a multiple cohort fisheries model with reserve size as the choice variable. Through a stock recruitment relationship, the model incorporates the impacts of a reserve on recruitment and harvest over time. Recruitment, growth, emigration, and immigration are density dependent. Harvest is a function of non-reserve stock, a small percentage of reserve stock assumed to be caught while foraging outside the reserve, and intensity of fishing effort. The overall level of fishing effort is assumed to be fixed, so that effort displaced from the reserve is applied to the portion of the fishery that remains open.⁸ The model does not account for spatial heterogeneity of stocks other than differences between reserve and non-reserve stocks.

Age structure of the population in the fishery is described using modified Leslie (1948) population matrices:⁹

$$\begin{aligned} \mathbf{X}(t) &= \mathbf{Z}^x(t-1)\mathbf{X}(t-1) + \mathbf{T}^{yx}(t-1)\mathbf{Y}(t-1) \quad \text{and} \\ \mathbf{Y}(t) &= \mathbf{Z}^y(t-1)\mathbf{Y}(t-1) + \mathbf{T}^{xy}(t-1)\mathbf{X}(t-1) \end{aligned} \quad (1)$$

where $\mathbf{X}(t)$ and $\mathbf{Y}(t)$ are $1 \times n$ row vectors of the numbers of fish of age a at time t in the fishery and reserve respectively, $\mathbf{Z}^x(t)$ and $\mathbf{Z}^y(t)$ are $n \times n$ matrices of recruitment, emigration and survivorship from age $a-1$ at time $t-1$ to age a at time t in the fishery and reserve, respectively, and $\mathbf{T}^{xy}(t-1)$ and $\mathbf{T}^{yx}(t-1)$ are $n \times n$ matrices of recruitment and immigration from age $a-1$ at time $t-1$ to age a at time t from the other stock.

Writing the elements of vectors, $\mathbf{X}(t)$ and $\mathbf{X}(t-1)$ and the matrices $\mathbf{Z}^x(t-1)$ and $\mathbf{T}^{yx}(t-1)$ provides a more detailed description of age structure:

⁷ Spawning Stock Biomass (SSB) does increase. However, without a stock recruitment relationship, this does not impact future recruitment.

⁸ This is similar to the way that Polacheck (1990) modeled effort except that effort was divided by the fraction of the incoming cohort protected by the reserve rather than the fraction of the fishery area closed.

⁹ For simplicity we develop and simulate a single species model. The assumption of single species limits the applicability of the model in multiple species fisheries. Multiple species models with interactions are extremely intractable. Fortunately, most target species exhibit similar spatial range and reproductive strategies. This suggests that the effects of the reserve will be similar for most of these species (Doherty and Williams 1988).

$$\begin{bmatrix} x(1, t) \\ x(2, t) \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ x(n, t) \end{bmatrix} = \begin{bmatrix} R^{xx}(1, t-1) & R^{xx}(2, t-1) & \dots & R^{xx}(n-1, t-1) & R^{xx}(n, t-1) \\ z^x(1, t-1) & 0 & \dots & 0 & 0 \\ 0 & z^x(2, t-1) & \dots & 0 & 0 \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ 0 & 0 & \dots & z^x(n-1, t-1) & 0 \end{bmatrix} \begin{bmatrix} x(1, t-1) \\ x(2, t-1) \\ x(3, t-1) \\ \cdot \\ \cdot \\ \cdot \\ x(n, t-1) \end{bmatrix}$$

$$+ \left\{ \begin{bmatrix} R^{yx}(1, t-1) & R^{yx}(2, t-1) & \dots & R^{yx}(n-1, t-1) & R^{yx}(n, t-1) \\ \tau^{yx}(t) & 0 & \dots & 0 & 0 \\ 0 & \tau^{yx}(t) & \dots & 0 & 0 \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ 0 & 0 & \dots & \tau^{yx}(t) & 0 \end{bmatrix} \begin{bmatrix} y(1, t-1) \\ y(2, t-1) \\ y(3, t-1) \\ \cdot \\ \cdot \\ \cdot \\ y(n, t-1) \end{bmatrix} \right\}$$

where n is maximum fish age; $R^{xx}(a, t - 1)$ is the rate of recruitment to the fishery at time t provided by an age a fish in the fishery at time $t - 1$; $R^{yx}(a, t - 1)$ is the rate of recruitment to the fishery at time t provided by an age a fish in the reserve at time $t - 1$; $\tau^{yx}(t)$ is the net emigration rate from the reserve to the fishery at time t ; $x(a, t)$ and $y(a, t)$ are the number of fish age a in the fishery and reserve, respectively, at time t ; and $z^x(a, t - 1)$ is the conditional probability of an age a fish surviving in the fishery from time $t - 1$ to time t .

An analogous description of the population dynamics for the reserve is described by interchanging x 's and y 's, and defining $R^{yy}(a, t - 1)$, $R^{xy}(a, t - 1)$, $\tau^{xy}(t)$, and $z^y(a, t - 1)$.

Recruitment is a function of overall (fishery and reserve) egg production and biomass density in the area of settlement (fishery or reserve). Recruitment is defined as survival to age one year rather than by vulnerability to fishing gear. The recruitment coefficients are specified as:

$$\begin{aligned} R^{xx}(a, t) &= (1 - S)B(D^x(t))L(w^x(a, t)) \\ R^{yx}(a, t) &= SB(D^x(t))L(w^y(a, t)) \end{aligned} \tag{2}$$

where $B(D^x(t))$ and $B(D^y(t))$ are the density dependent recruitment rates for the fishery and reserve respectively; $D^x(t)$ and $D^y(t)$ are the biomass density of the fishery and reserve, respectively, at time t ; $L(w(a, t))$'s are weight dependent egg/larva production rates; S is reserve size as a percentage of the total pre-reserve fishing area; and $w^x(a, t)$ and $w^y(a, t)$ are the weights of an age a fish in the fishery and reserve, respectively, at time t . $B(D^y(t))$ is defined analogously.

Eggs and/or larvae are assumed to leave the reserve and the fishery, mix, and be

distributed uniformly over the reserve and fishery upon return.¹⁰ The fishery and reserve receive proportions $1 - S$ and S , respectively, of total larvae but survival of those larvae to recruitment at age 1 is dependent on local biomass density. If recruitment is purely local, then the only interaction between the reserve and fishery will be through emigration and immigration and the R^{xy} and R^{yx} coefficients will be zero and the R^{xx} and R^{yy} coefficients will be multiplied by one rather than S and $(1 - S)$ respectively.

The fishery (reserve) biomass density at time t is the total weight of the fishery (reserve) at time t divided by size of the fishery (reserve):

$$D^x(t) = \frac{W^x(t) \cdot X(t)}{1 - S}; \quad D^y(t) = \frac{W^y(t) \cdot Y(t)}{S} \quad (3)$$

where $W^x(t)$ and $W^y(t)$ are $n \times 1$ row vectors of age specific weights, $w^x(a, t)$ and $w^y(a, t)$, respectively. Growth rates are assumed to be density dependent. That is, fish weight is determined by age of fish and population density.¹¹

After recruitment, the number of age a fish in the fishery (reserve) depends on the survivorship of age $a - 1$ fish in the fishery (reserve) at time $t - 1$ plus net immigration from the reserve (fishery). The hazards to survivorship are natural mortality and fishing mortality. The conditional probability of surviving in the fishery and the reserve from age $a - 1$ to age a can be decomposed into:

$$z^x(a - 1, t - 1) = 1 - M^x(a - 1) - \left(\frac{D^x(t - 1)}{D^y(t - 1)} \right) \tau^{xy} - F^x(a - 1) \frac{E}{1 - S} \quad (4)$$

$$z^y(a - 1, t - 1) = 1 - M^y(a - 1) - \left(\frac{D^x(t - 1)}{D^y(t - 1)} \right) \tau^{yx} - F^y(a - 1) \frac{E}{1 - S}$$

where E is the predetermined effort level,¹² $F^x(a - 1)$ and $F^y(a - 1)$ are the fishing mortality rate of fish of age a in the fishery and reserve, respectively, and $M^x(a - 1)$ and $M^y(a - 1)$ are the natural mortality rate of fish of age a in the fishery and reserve, respectively.

Natural mortality is an age specific coefficient. Adults of the target species are assumed to show high fidelity to base locations though they move within a limited range to feed. Emigration rates are assumed to be responsive to resource limitations. To capture these limitations we multiplied the base transfer rates τ^{xy} and τ^{yx} by the ratio of the population biomass densities of the fishery and the reserve to get $\tau^{xy}(t)$ and $\tau^{yx}(t)$, the emigration rates at time t . That is, the greater the relative density of the reserve to the fishery, the lower the emigration rate from the fishery to the reserve, is and the higher the emigration rate from the reserve to the fishery.¹³

¹⁰ There is a great deal of scientific disagreement over the spatial pattern of recruitment after the larval stage. The simulation examines the extreme cases of uniform dispersal and local recruitment. A range of other possibilities exist which could be captured fully only in an explicitly spatial model.

¹¹ There is limited support for density dependent growth rates (Doherty and Williams 1988). Due to an increase in density within the reserve, density dependent growth reduces the value of the reserve; simulations with density independent growth produced significantly larger optimal reserve sizes.

¹² The effort level E is a multiplier on the fishing mortality rate, generally ranging from 0 to 3. It does not represent a particular quantity of effort.

¹³ Using density independent emigration is a simpler alternative. In the simulation when we replaced only density dependent emigration with density independent emigration the changes in the results were small. When density independent emigration is combined with density independent growth, then optimal reserve sizes and present value of harvests increase significantly.

Fishing mortality is a vector of age specific fishing mortality rates multiplied by intensity of effort (a scalar) divided by the size of the fishery (proportion of the pre-reserve fishery open to fishing).¹⁴ This implies that total effort remains constant, and all effort displaced by the introduction of a reserve is transferred to the open fishing area so that the intensity of effort in the area remaining open increases.¹⁵ Age specific fishing mortality allows for, but does not imply initial and continuing management conditions that control size selectivity of catch.

The optimal reserve size maximizes the present value of harvest (PVH) weight over the planning horizon:

$$PVH = \max_S \sum_{t=0}^{\infty} \left(\frac{1}{1+i} \right)^t P[W^x(t)F^x X(t) + W^y(t)F^y Y(t)] \cdot \frac{E}{1-S} \quad (5)$$

where F^x and F^y are $n \times n$ fishing mortality matrices with age specific mortality coefficients $F^x(a)$ and $F^y(a)$ along the diagonal and zeros elsewhere, i is the discount rate, P is fish price per unit and S is reserve size as percentage of total fishing area.

$S = 1$ implies that the entire area is closed to fishing. $S = 0$ indicates that the reserve size is zero. Thus:

$$0 \leq S < 1 \quad (6)$$

The optimal reserve size depends on the initial stocks and age class structure of the fishery and reserve. For simplicity we assume that the age structure of fish is known, and that the initial number of fish in each age class of the fishery (reserve) are equal to the number of fish in each age class of the fishery before imposing the reserve multiplied by the percentage of the original fishery area the post reserve fishery (reserve) take up.

The initial age class structures are:

$$X(0) = \frac{N_0}{1-S}; Y(0) = \frac{N_0}{S} \quad (7)$$

where N_0 is a vector of fish in the fishery at time 0 by age prior to introduction of the reserve, and X_0 and Y_0 are vectors of the initial age class distributions for the fishery and reserve, respectively.

The optimal reserve size is the maximum of (5) with respect to reserve size subject to the population dynamics equations (1), the reserve size constraint (6), and initial stocks (7). Reserve size S is specified as a constant, so static optimization methods are used. We apply the Kuhn-Tucker conditions (Kuhn-Tucker 1951).

The Lagrangian function is:

¹⁴ Effort is a scaling factor that adjusts fishing mortality to reflect changes in effort while keeping intact the proportionality of fishing mortality rates between age classes that is consistent with the gear selectivity and fishing practices in the fishery.

¹⁵ The other extreme is to assume that none of the effort displaced by the introduction of a reserve is transferred to the open fishing area. That is, total effort drops proportionally with the size of the reserve, and intensity of effort is constant. Constant intensity is more likely to be true when reserves are of large absolute size, while increased intensity is more likely with small reserves. The increased intensity assumption corresponds with the experience of the Sumilon Reserve (Alcala 1988) and with the Polacheck (1993) model.

$$\begin{aligned}
 PVH = \sum_{t=0}^{\infty} \left\{ \left(\frac{1}{1+i} \right)^t \right\} & P[W^x(t)F^x X(t) + W^y(t)F^y Y(t)] \cdot \frac{E}{1-S} \quad (8) \\
 & + \Theta^x(t) [X(t) - Z^x X(t-1) - T^{yx}Y(t-1)] \\
 & + \Theta^y(t) [Y(t) - Z^y Y(t-1) - T^{xy}X(t-1)] \\
 & + \lambda S + \Phi^x \left[X(0) - \frac{N_0}{1-S} \right] + \Phi^y \left[Y(0) - \frac{N_0}{S} \right].
 \end{aligned}$$

where $\Theta^x(t)$ and $\Theta^y(t)$ are vectors of multipliers that may vary over time, λ^{16} is a scalar multiplier, and Φ^x and Φ^y are vectors of multipliers on the initial conditions.

The optimal reserve size must satisfy:¹⁷

$$\begin{aligned}
 L_s = \sum_{t=0}^{\infty} \left\{ \left(\frac{1}{1+i} \right)^t \right\} & P[W^x(t)F^x X(t) + W^y(t)F^y Y(t)] \cdot \frac{E}{(1-S)^2} \quad (9) \\
 & - \Theta^x(t) [Z_s^x X(t-1) + T_s^{yx} Y(t-1)] \\
 & - \Theta^y(t) [Z_s^y Y(t-1) + T_s^{xy} X(t-1)] \\
 & + \lambda - \Phi^x \frac{N_0}{(1-S)^2} + \Phi^y \frac{N_0}{S^2} = 0.
 \end{aligned}$$

Expanding using equations (3) and (4), the elements of the second through n th rows of z_s^x and z_s^y are:

$$\begin{aligned}
 z_s^x(a) &= \tau^{xy} \left[\frac{D_s^y D^x - D_s^x D^y}{(D^y)^2} \right] - F^x(a) \frac{E}{(1-S)^2} \\
 z_s^y(a) &= \tau^{yx} \left[\frac{D_s^x D^x - D_s^y D^y}{(D^y)^2} \right] - F^y(a) \frac{E}{(1-S)^2}
 \end{aligned}$$

The elements of T_s^{xy} and T_s^{yx} are the negative of the first element of the corresponding row of Z_s^x and Z_s^y . The first row of the Z_s^x and Z_s^y matrices are found by differentiating the recruitment coefficients with respect to S . In addition to (9), conditions (1), (6), and (7), represented by the product of the right-hand side of the condition and the respective multipliers, $\Theta^x(t)$, $\Theta^y(t)$, λ , Φ^x , and Φ^y set equal to zero, are also necessary for a maximum.

The first term of (9) is the discounted marginal revenue product of yield with respect to reserve size. This term is always positive since the introduction of a reserve always increases the intensity of effort in the area open to fishing. The second term is the loss in the value from protecting the marginal fish formerly in the fishery

¹⁶ Setting the revenues equal to zero when $S = 1$ implies that optimal reserve size will always be less than 1.
¹⁷ For simplicity, we assume that second-order sufficiency conditions for a maximum are satisfied.

and now in the reserve. The third term is the gain in the value from protecting the marginal fish in the reserve. The fourth term is the value of the nonnegativity constraint for reserve size. The last two terms are the marginal values of including the initial stock either in the fishery or reserve, respectively.

If the nonnegativity constraint is binding, then $S = 0$. This implies that the value of the reserve is negative. If the marginal gain from a reserve decreases with reserve size, then the marginal loss in value from fish in the fishery from the introduction of a reserve exceeds the marginal gain in value from protecting some fish in a reserve for all reserve sizes.

If the constraint is nonbinding, then $0 < S < 1$, and the value of the reserve is positive for some range. The marginal gain in value from protecting some fish in a reserve exceeds the marginal loss in value from reducing the open area of the fishery within this range.

A new and potentially important result arises from the magnitude of the interest rate. The higher the discount rate, the greater the weight placed on the initial periods relative to later periods. Since introduction of a reserve causes short term harvests to fall, this implies the higher the interest rate, the smaller the optimal reserve will be. This result can be demonstrated using standard comparative statics (Samuelson 1947; Silberberg 1990). A sketch of the proof follows from noting that the only appearance of the interest rate i in the necessary conditions is in (9). The partial derivative of (9) with respect to i is negative, which is the same sign as required by the second-order conditions of the derivative of (9) with respect to S . Applying comparative statics methodology then shows that optimal reserve and the interest rate are inversely related.

Since total effort is assumed fixed, costs of fishing do not change the net present value of harvests. Only when the discount rate is zero is the optimal steady-state the maximum sustainable yield. This result is in the spirit of Plourde (1970).

Simulation Methodology

The purpose of the simulation is to describe the impacts of a range of effort levels and commonly held biological assumptions on optimal reserve size and the present value of the fishery. Key parameters include effort level, discount rate, recruitment rates, emigration rates, and growth rates. Due to the uncertainties regarding many of the biological parameters, the simulation results are not expected to yield accurate quantitative data on the impacts of reserves, but are meant to illustrate implications of different sets of plausible assumptions. The results are not meant to predict outcomes for any specific fishery.

To simulate the age specific growth rates, natural and fishing mortality, and fecundity of an inshore, reef fishery, we use data from red snapper in the Gulf of Mexico (Goodyear 1992). Snapper are an important target species in many reef fisheries and have biological, behavioral, and reproductive characteristics in common with several other important target species in reef fisheries (Bohnsack 1990). These characteristics include: a pelagic larval stage, limited movement of adults, slow growth, low natural mortality, and an exponential relationship between weight and fecundity. For fisheries with these characteristics, a reserve may allow an older, larger, and more fecund¹⁸ population to develop which by increasing recruitment may more than compensate for fishing area lost to the reserve.

¹⁸ For many important fish species, larger fish have many, many times the eggs of smaller specimens. For instance one 23.8 inch red snapper will produce as many eggs as 212 females of 16.4 inches (Bohnsack 1990).

The simulation procedure begins with a steady state population structure corresponding to a particular level of fishing effort and age structure of catch and no reserve. A reserve is then imposed, closing a fraction of the area of the fishery. Following equation (1), fish are separated by age class and location inside or outside the reserve. Following equation (2), we incorporate a compensatory, Ricker-like stock recruitment relationship; the increase in spawning stock biomass (SSB) of the reserve population over time is reflected in increased recruitment in both the reserve and fishery.¹⁹ STELLA,²⁰ a simultaneous difference equation solver, is used to describe the time path of the fishery and reserve populations and harvests. Population and fishery dynamics are simulated until a new steady state is reached. All runs reached a new equilibrium steady-state by year 60.

Effort levels in the simulation are multiples of a base set of age specific fishing mortality rates taken from red snapper data from the Gulf of Mexico (Goodyear 1992). An effort level of 0.75 corresponds roughly with an instantaneous fishing mortality, F , equal to 0.27, which is asserted to achieve maximum sustainable yield (MSY) with controllable effort in the absence of a reserve policy (Goodyear 1992). An effort level of 1.0 corresponds with a lightly- to moderately-fished fishery, 1.5 moderate- to heavily-fished, 2.0 heavily-fished, and 2.5 very-heavily. The 1.0 level corresponded with the age specific fishing mortalities under the management conditions of the time which was open access but included size regulations.

To simulate the reserve size that maximizes the present value of harvests (PHV) over time for different levels of effort, a grid-search procedure is used.²¹ Since there is incomplete information and disagreement about some of the biological assumptions, the simulation was repeated with different assumptions concerning the discount rate, larval mixing, recruitment, emigration, and growth.

Simulation Results

Table 1 and figure 1 show the present value of cumulative harvests (PVH) over the 60 year planning horizon, for various reserve sizes and levels of effort. The optimal reserve size for each effort level is indicated in the last column. Values in the table and figures are percentages of the levels achieved with a 0.75 effort level and no reserve. Optimal reserve sizes vary greatly with the level of fishing effort. No combination of effort level and reserve size achieves a PVH higher than the MSY (0.75) effort level. At low to moderate initial levels of fishing effort (0.75 and 1.0) optimal reserves sizes are negligible (0 and 0.01). At high levels of fishing effort (1.5 and 2.0) optimal reserve sizes ranges from 15% to 19% of the fishery area; PVH increases by 3.6% to over 8% compared with no reserve. At a very high level of fishing effort (2.5), the fishery collapses in the absence of a reserve. However, even at this very high level of effort, the PVH of the fishery can be brought back to 75% of the MSY level with a reserve covering 29% of the fishery. The new equilibrium yield is nearly 95% of MSY.

If effort can be controlled, marine reserves provide little or negative benefits. At low fishing intensities, reserves reduce fishery production, both in the short run and

¹⁹ Recruitment is deterministic. Stochastic recruitment makes interpretation of simulation results extremely difficult.

²⁰ STELLA™ is an icon based programming package developed by High Performance Systems.

²¹ In the grid search procedure, we first simulated PVH from equation (5) under several reserve sizes subject to (1), (6), and (7). We then decreased the step size in the range of reserve sizes that had the maximum PVH. We repeated the process until the optimal reserve size was reached. We used this procedure rather than simulating (9) subject to (1), (6), and (7) because it avoided potential convergence problems and was much faster.

Table 1
Minimum Annual Harvest, New Equilibrium Annual Harvest, and Present Value of Cumulative Harvest up to year 60, with Varied Reserves Sizes and Effort Levels

Reserve Size (S)	$S = 0$	$S = 0.1$	$S = 0.2$	$S = 0.3$	Optimal Reserve Size
Effort Level $E = 0.75/(1 - S)$					Optimal $S = 0$
Min harvest	100	93.6	86.7	79.2	100
New equilibrium	100	97.5	93.6	89.1	100
PV harvest	100	97.3	93.6	88.9	100
Effort Level $E = 1.0/(1 - S)$					Optimal $S = 0.01$
Min harvest	96.8	91.9	86.5	80.6	96.3
New equilibrium	96.8	97.0	94.1	89.5	97.0
PV harvest	96.8	95.8	93.0	88.7	96.8
Effort Level $E = 1.5/(1 - S)$					Optimal $S = 0.15$
Min harvest	89.2	83.8	78.0	71.7	81.0
New equilibrium	89.2	93.0	93.2	89.4	94.3
PV harvest	89.2	91.9	92.0	90.2	92.4
Effort Level $E = 2.0/(1 - S)$					Optimal $S = 0.19$
Min harvest	84.5	78.8	72.7	66.2	73.3
New equilibrium	84.5	91.3	94.9	95.9	94.9
PV harvest	84.5	89.6	91.7	91.3	91.7
$E = 2.5/(1 - S)^a$					Optimal $S = 0.29$
Min harvest	COLLAPSE	23.0	21.1	19.4	19.5
New equilibrium	COLLAPSE	90.1	94.9	94.9	95.3
PV harvest	COLLAPSE	66.0	73.8	75.8	75.8

Notes: All values in the table are a percentage of the maximum value achievable with no reserve, roughly the maximum sustainable yield. Minimum harvest occurs when the reserve is first imposed. Harvests recover to near new equilibrium levels within 6 to 8 years, though stabilization at the new equilibrium takes longer. Equilibrium was reached by year 60 in all cases. A discount rate of 5% is used throughout.

^a Assumes starting population approximately equal to 25% of the fishery at the 2.0 effort level with no reserve.

long run. At the MSY level (0.75), effort reserves of 20% to 30% reduce the PVH by 6.4% to 11.1%.

Another consideration in many fisheries may be the level to which harvest falls when the reserve area is first closed. When the fishery is a critical source of income or sustenance for a community, a dramatic drop in harvests may not be acceptable even if it is temporary. Thus minimum harvest may be a constraint on optimal reserve size. Minimum annual harvests level as a function of reserve sizes for different effort levels are presented in table 1.²² These values are as a percentage of the MSY annual harvest level. Annual harvests fall to these minimum levels when the reserve is first imposed and take six to nine years to recover to levels near the new equilibrium. As indicated in table 1, when 20% of the fishery area is closed, annual harvests initially fall by 10% to 14% depending on effort levels.

²² An alternative to limiting reserve size is to gradually increase the reserve size over time to ensure a minimum harvest level is maintained.

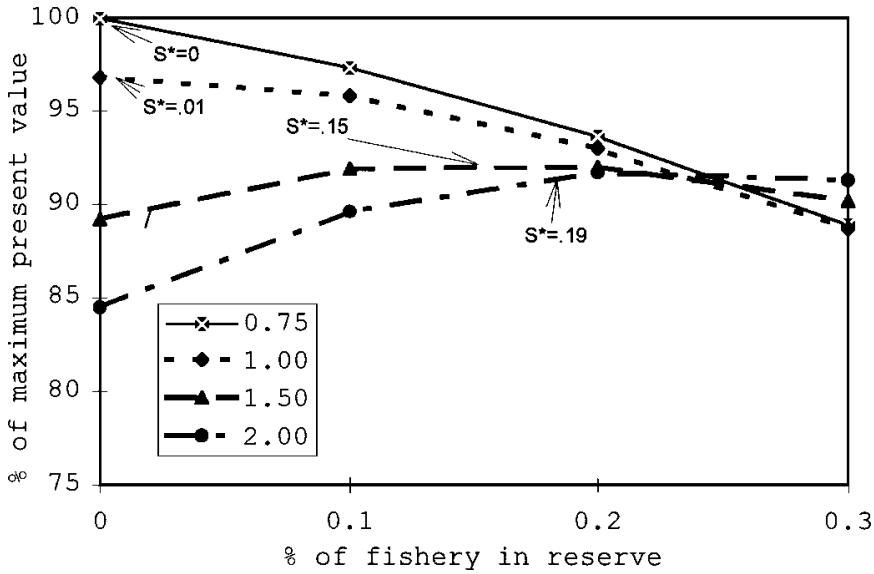


Figure 1. Present Value of Cumulative Harvest (through year 60) for Various Reserve Sizes and Effort Levels. S^* indicates the optimal reserve size for the respective effort levels

Sensitivity to Economic Assumptions

When a reserve is instituted, fishery harvests initially fall as a portion of the population is removed from the fishery. Over time harvests increase as the older, more fecund population of the reserve supplements recruitment in the fishery, and some large fish emigrate from the reserve. The higher the discount rate the more the early losses are weighted relative to future gains. As discussed earlier, this implies that a higher interest rate decreases the optimal reserve size. For example at the 1.5 level of effort, the optimal reserve size falls from 18% to 0% when the discount rate is raised from zero to 20%.²³ For a zero discount rate reserve size is chosen to maximize steady-state harvest. In table 1, the rows labeled “new equilibrium” show the harvest level (as a percentage of the MSY level) when the new equilibrium is reached. This approximates (as the planning horizon goes to infinity) the present value of various reserve sizes when the discount rate is zero.

Cost of fishing effort may also affect the performance of reserves. Here we assume that overall fishing effort remains constant for all reserve sizes. If effort levels drop when part of the fishery is closed, the value of reserves may be greater than our simulation results indicate. If total fishing effort increases in a rent dissipating fashion, any economic gains may be dissipated. Fishing costs may also be increased and the value of reserves decreased, if fishers who were fishing in the closed area prior to creation of the reserve have to travel further to fish in the unclosed area. Enforcement costs, although likely to be small compared to many other methods of regulation (Bohnsack 1990), will also decrease the value of reserves.

²³ Discount rates of poor in developing countries tend to be high (Chapman 1993; Clark 1991) thus rates of 10%, 20%, or higher may be appropriate for artisanal fishers who are typically poor. Many people argue, however, that very low discount rates should be used to ensure preservation of resources for future generations.

Elasticity of fish prices may also impact the usefulness of reserves. If fish prices are elastic, then both gains from increased production and early losses (to income if not to nutritional needs of the population) will be reduced. The impact on optimal reserve size will depend on the demand function and discount rates. To examine the impact of demand elasticity, we introduced a linear demand curve with a slope of -1 . The impacts on value of the fishery and optimal reserve size was minimal. For example at the 1.5 effort level with a 5% discount rate, the optimal reserve size fell by only 1%. If prices are increasing over time, the optimal reserve size will be higher than with constant prices. This has the same effect as lowering the discount rate if price is increasing at a constant rate.

The value of reserves may also be affected by price schedules linked to individual fish size. With an effort level of 1.5, average fish size decreases from 1.61 to 1.51 pounds per fish, while the catch rate of large fish, ages 8 to 10, increased slightly due to immigration from the reserve. However, the age and size structure for most of the catch was reduced due to the increased intensity of effort when effort from the closed area was redistributed.

Sensitivity to Biological Assumptions

The simulation results are also sensitive to several biological assumptions. Unfortunately, the population dynamics of reef fisheries are not well understood. To examine the effects of this lack of certainty on the effectiveness of reserves we vary the assumptions of the stock recruitment relationship, the base transfer rates, and the response of growth and transfer rates to increased biomass density.

An important assumption for the effectiveness of reserves is the connection between egg production, dispersal, and recruitment. The geographical spread of larvae and subsequent recruitment is not well understood. However, it is clear that if larval distribution and recruitment are more localized, many small reserves will be preferred to one large one. In the results presented we assume that larvae are uniformly mixed throughout the reserve and fishery. With at least some spatial mixing of recruitment across the fishery, results may be robust with respect to the actual geographical spread of recruits since no particular spatial designs for reserves are assumed in the model. However, for the design of actual reserves, their shape and location might be very important.

Local recruitment in which the reserve population provides recruits only for the reserve, and the fishery for only the fishery, is the opposite of uniform mixing of recruits. This is equivalent to replacing the elements of the first row of the \mathbf{T}^{xy} and \mathbf{T}^{yx} matrices in (1) with zeros. With local recruitment, reserves are not effective in improving the PVH even with high transfer rates. However, while reserves do not increase the productivity of the fishery, they do not decrease it much either. With an effort level of 1.5, discount rate of 0.05, and a base transfer rate of 0.05, the PVH of the fishery drops less than 2% (4%) with a reserve size of 10% (20%).

Assumptions regarding the response of recruitment, growth and transfer rates to changes in localized biomass density also impact the results of the model. The initial simulations allowed all three (recruitment, growth, and transfer) rates to vary with localized biomass density. A subsequent simulation with an effort level of 1.5 tightened the assumptions of density effects on both growth and transfer; that is, growth and transfer were made density independent. The transfer vectors $\mathbf{T}^{xy}(t)$ and $\mathbf{T}^{yx}(t)$ were replaced by the vector of constants, \mathbf{T}^{xy} and \mathbf{T}^{yx} .²⁴ With density independent

²⁴ This implies that resource limitations or crowding either do not occur or do not affect fish behavior or growth.

growth and density independent emigration optimal reserve sizes and harvests increased, particularly at moderate and high effort levels. However, inclusion of either density dependent growth or density dependent emigration yielded similar results to the simulations which included both density dependent growth and density dependent emigration. This implies that if both growth and emigration rates are density independent that the reported increases in simulated optimal reserve size and PVH are conservative.

Emigration rates were varied through changes in the rate of transfer and sensitivity to relative densities. However, the impacts on the dynamic optimum reserve size and the PVH were very small.

Conclusions

Conventional regulatory methods that depend on reducing fishing effort or regulating catch are expensive and difficult or impossible to apply effectively in many fisheries. Large numbers of fishers and landings sites can make monitoring very expensive in many fisheries, particularly artisanal fisheries (Holland, *et al.* 1995). Often the technical capabilities for stock assessment are not sufficient to determine appropriate effort or catch rates. In other cases, reducing effort can be politically impossible. Although not a first-best solution, marine reserves provide a feasible alternative management strategy for some fisheries. The results presented support the hypothesis that marine reserves can be effective in sustaining or increasing fishery yields for moderate- to heavily-fished reef fisheries under a variety of assumptions regarding the biological parameters. The results clearly support the use of marine reserves in heavily fished fisheries where effort reductions are not feasible. These results contrast with previous simulation results provided by equilibrium yield per recruit models that did not incorporate age class dynamics and a stock recruitment relationship.

While the results are subject to biological uncertainties, some apparently robust conclusions are: (i) The effects of a reserve and the optimal size will vary with the level of effort. Higher effort levels require larger reserves sizes to achieve maximum value from the fishery. If effort levels are low, reserves will probably not improve yields, and large reserves may significantly decrease fishery production; (ii) Initially fishery production will fall and will take several years to recover. Thus the discount rate of those affected as well as minimum production requirements are critical to policy decisions about reserves. High discount rates will both lower the value of reserves and decrease the optimal size. Constraints on minimum production may also limit the size of reserves; and (iii) For fisheries with extremely high levels of fishing effort, reserves can provide insurance against collapse of the fishery. The reduction in risk to the fishery together with existence and amenity values provided by the reserve add to the value of reserves and may make reserves more desirable. If enforcement costs are low, and, as the analysis indicates, this insurance can be bought at little or no cost in foregone annual harvest, reserves may prove worthwhile.

Although our results indicate that marine reserves may be useful in increasing harvest biomass in some heavily fished fisheries, reserves by themselves cannot be expected to maximize rents in the fishery. In fact all rents may be dissipated if effort expands in response to higher catches. It appears that if catch or effort can be cost effectively controlled, reserves will provide little or no benefit in terms of increased harvest revenues. This is particularly true if regulations are effective at controlling minimum size of fish caught.

Our analysis also suggests that the primary benefits of reserves will come from

increased or more stable recruitment, due to an increase in SSB.²⁵ Empirical analysis of tropical and temperate reef fisheries indicate the reserves are effective in protecting a fish stock (Roberts and Polunin 1993; Cole, *et al.* 1990). There is some evidence, both empirical and from modeling, that reserves may increase spawning stock biomass for groundfish such as cod and flatfish (Polacheck 1990; Cadrin, *et al.* 1995; Doll 1996). It seems less likely that reserves will provide benefits for highly migratory fish, though experience with bird sanctuaries suggest that a system of reserves might provide some protection to these stocks.

Marine reserves have historically been created to protect biodiversity, preserve pristine habitat, and to attract tourists. Decisions on whether to establish a reserve have required a comparison of these benefits with the cost to fisheries in foregone harvest. The scope for implementation of marine reserves is greatly increased, if they can protect biodiversity and habitat while simultaneously maintaining or enhancing fishery production. Further investigation is needed to provide more quantitative information about optimal design of reserves and to determine if reserves will be useful for the management of selected fisheries.

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²⁵ Whether increases in SSB will translate into increase recruitment is of course a critical question and one on which there is little agreement or evidence.

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