

Managing fisheries without restricting catch or effort : the use of marine reserves for inshore fisheries

Daniel S. Holland^{1[a]1}

Department of Environmental & Resource Economics
University of Rhode Island

Abstract

Although widely accepted, management systems that directly restrict catch or effort are neither efficient nor desirable for many fisheries, and have failed to conserve fishery stocks in many cases. Fisheries scientists have suggested that closing part of the fishery with marine reserves may sustain or increase harvest. These marine reserves act as natural hatcheries and nurseries in which reproduction and growth are not impeded, and supplement the surrounding fishery. Empirical studies of marine reserves have focused on the conservation benefits only inside the reserves. I develop a dynamic model and numerical simulation of a fishery for which a marine reserve is introduced. Net present value of fish harvests are maximized as a function of reserve size with total effort assumed constant. Unlike previous models, the time path of harvests and fish stocks prior to reaching a new steady-state is determined. This is important because the full impact of the reserve may not be realized for several years. The model suggests that reserves may increase the net present value of the fishery when total effort is high and can not be regulated directly. Higher discount rates reduce the optimal size of reserves.

Introduction

Conventional methods of regulating commercial fisheries including 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 fish stocks (For example, see Roberts and Polunin 1991). In some fisheries due to the large number of fishers, a variety of fishing technologies or complex inter-specific interactions, these methods of regulation are difficult and/or expensive to use.

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 basei[1]. Marine reserves will likely be most effective for sustaining or increasing harvests in inshore fisheriesii[2] in which adults are non-migratory residents. However, reserves may be useful for other fisheries as welliii[3].

My purpose is to present a simple, economic analysis of marine reserves as a tool of fishery management. This is a first step in addressing an important omission in the literature. Previous models of marine reserves have been yield per recruit analyses. 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 (Polacheck 1990, DeMartini 1993).

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).iv[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.

I begin with a dynamic model of a fishery in which a marine reserve is introduced. The structure of the model is detailed in an appendix. In contrast to most previous economic models of fisheries, total effort is assumed to be fixed. Unlike previous models of marine reserves the optimal reserve size is determined by maximizing net 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.v[5] 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 model in the appendix is a simplified description of the introduction of a reserve, due to the complexities of modeling age structure, unambiguous qualitative results are scarce. To investigate more fully introducing reserves and to begin examining the potential quantitative impacts from introducing reserves, I 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.vi[6] The sensitivity analysis illustrates the importance of key biological assumptions.

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 net present value of a 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.

To simulate the age specific growth rates, natural and fishing mortality, and fecundity of an inshore, reef fishery, I 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 fecund population to develop, which by increasing recruitment may more than compensate for fishing area lost to the reserve.

The simulation procedure begins with a steady state population structure corresponding to a particular level of fishing effort and no reserve. A reserve is then imposed, closing a fraction of the area of the fishery. Following equation (1) from the appendix, fish are separated by age class and location inside or outside the reserve. Following equation (2), I incorporate a compensatory, Ricker-like stock recruitment relationship; the increase in spawning stock biomass of the reserve population over time is reflected in increased recruitment in both the reserve and fishery [8]. STELLA [9], 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 7.5 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.

To simulate the reserve size that maximizes the NPV of harvest over time for different levels of effort a grid-search procedure is used. [10] Since there is incomplete information and disagreement about some biological assumptions, the simulation was repeated with different assumptions concerning the discount rate, larval mixing, recruitment, emigration, and growth.

Simulation Results

The net present value of harvests and optimal reserve sizes for several effort levels are presented in Table 1 and Figure 1. Optimal reserve sizes vary greatly with the level of fishing effort. No combination of effort level and reserve size achieves discounted cumulative production higher than the MSY level. At low to moderate initial levels of fishing effort (.75 and 1.0) optimal reserves sizes are negligible (0 and .01) and do not increase the NPV of fishery compared to the absence of reserves. At high levels of fishing effort (1.5 and 2.0) optimal reserve sizes ranges from 15% to 19% of the fishery area; NPV increases by 3.6% to over 8%. 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 NPV of the fishery can be brought back to 75% of the maximum value with a reserve covering 29% of the fishery, and the new equilibrium yield is nearly 95% of MSY.

If effort can be controlled, marine reserves provide little or negative net benefits. At low fishing intensities, reserves reduce fishery production significantly, both in the short run and long run. At the MSY level (.75) of effort annual production reserves of 20-30% reduces the NPV of cumulative harvests fall by 6.4% to 11.1%.

Another consideration in many fisheries may 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.xi[11] Annual harvests fall to these minimum levels when the reserve is first imposed and take 6 to 9 years to recover to levels near the new equilibrium. As Table 1 shows, when 20% of the fishery area is closed, annual harvests initially fall by 10 to 14 percent depending on effort levels.

Table 1 2[b]: Minimum annual harvest3[c], new equilibrium annual harvest4[d], and net present value of cumulative harvest up to year 605[e], with varied reserve sizes and efforts levels.

RESERVE SIZE (S)	S=0	S=.1	S=.2	S=.3	Optimal reserve size
EFFORT LEVEL $E=.75/(1-S)$				Optimal S=0	
min harvest	100	93.6	86.7	79.2	100
new equilibrium	100	97.5	93.6	89.1	100
NPV harvest	100	97.3	93.6	88.9	100
EFFORT LEVEL $E=1.0/(1-S)$				Optimal S=.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
NPV harvest	96.8	95.8	93.0	88.7	96.8

EFFORT LEVEL $E=1.5/(1-S)$					Optimal $S=.15$
min harvest	89.2	83.8	78.0	71.7	81.0
new equilibrium	89.2	93.0	93.2	89.4	94.3
NPV harvest	89.2	91.9	92.0	90.2	92.4
EFFORT LEVEL $E=2.0/(1-S)$					Optimal $S=.19$
min harvest	84.5	78.8	72.7	66.2	73.3
new equilibrium	84.5	91.3	94.9	95.9	94.9
NPV harvest	84.5	89.6	91.7	91.3	91.7
$E=2.5/(1-S)$ ^{6[f]}					Optimal $S=.29$
min harvest	COLLAPSE	23.0	21.1	19.4	19.5
new equilibrium	COLLAPSE	90.1	94.9	94.9	95.3
NPV harvest	COLLAPSE	66.0	73.8	75.8	75.8

Figure 1: Net Present Value of Cumulative Harvest for Various Reserve Sizes and Effort Levels

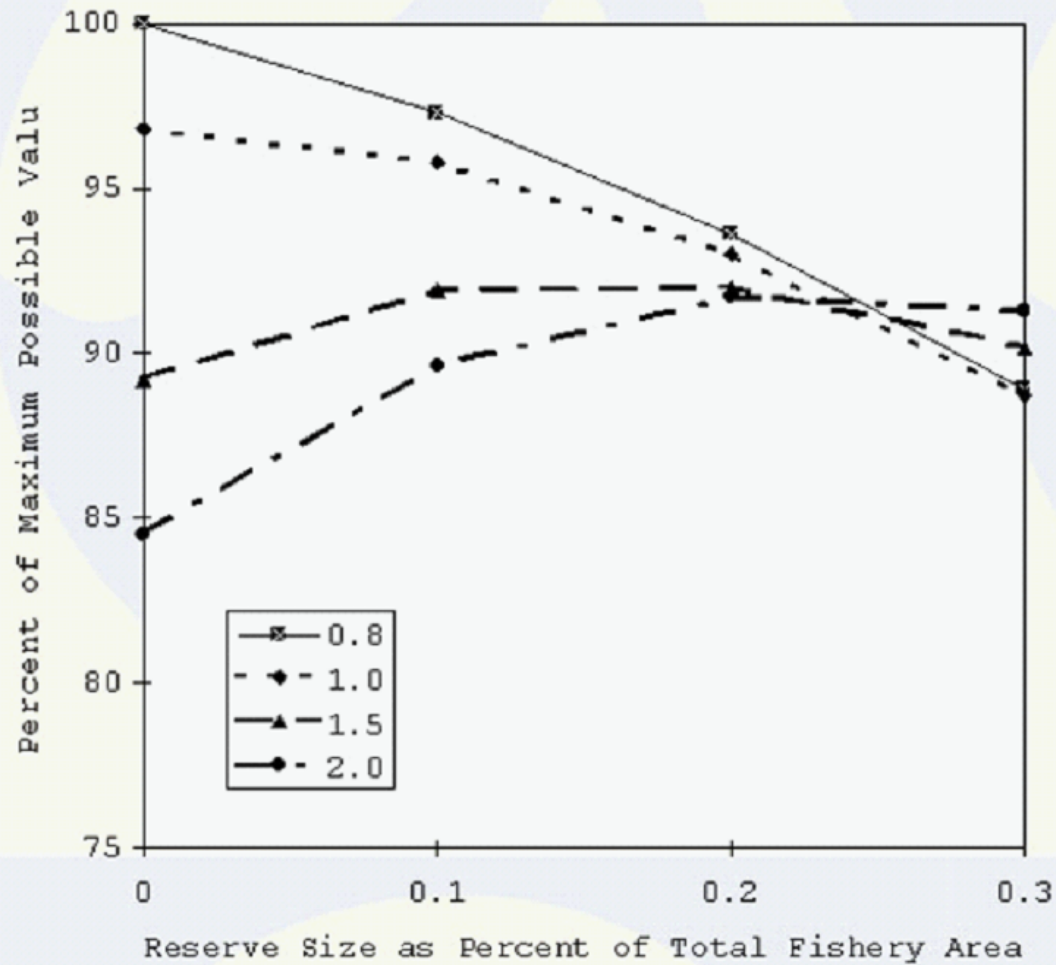


Figure 1: The above figure shows, for a variety of reserves sizes and base effort levels, the net present value of cumulative harvests from the time the reserve is implemented through year sixty (by which time a new equilibrium has been reached).

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 relatively 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 zero when the discount rate is raised from zero to 20% [12]. For a zero discount rate reserve size is chosen to maximize steady-state harvest. In Table 1, the rows labeled "new equilibrium" essentially show the net present value of various reserve sizes when the discount rate is zero.

Cost of fishing effort may also affect the performance of reserves. Here I 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 my 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 small compared to many other methods of regulation, will also decrease the value of reserves.

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, I 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%.

Biological Assumptions

The simulation results are also sensitive to several biological assumptions.

Unfortunately, the population dynamics and behavioral patterns of reef fisheries are not well understood. To examine the effects of this lack of certainty on the effectiveness of reserves I 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 I 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 α_{xy} and α_{yx} matrices in equation (1) from the appendix with zeros. With local recruitment, reserves are not effective in improving the NPV of harvests 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 .05 and a base transfer rates of .05, the net present value of cumulative yield from 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 $\alpha_{xy}(t)$ and $\alpha_{yx}(t)$ were replaced by the vector of constants, T_{xy} and α_{yx} [13]. With density independent 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 NPV of harvests 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 NPV of cumulative harvests 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. 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. Although, due to the lack of accurate data, information about absolute levels of production and reserve sizes is not reliable, the results clearly support the use of marine reserves in fisheries with high levels of fishing effort. This contrasts with previous simulation results provided by equilibrium, yield per recruit models that did incorporate age class dynamics.

While the results are subject to biological uncertainties, some apparently robust conclusions are:

- 1) 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.

2) 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.

3) For fisheries with extremely high levels of fishing effort, reserves 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 value of reserves and may make reserves desirable even if harvests are reduced somewhat.

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.

References

Alcala, Angel C. 1988. "Effects of Marine Reserves on Coral Fish Abundances and Yields of Philippine Coral Reefs." *Ambio* 17(3): 194-199.

Bohnsack, J.A. 1982. "Effects of Piscivorous Predator Removal on Coral Reef Fish Community Structure." In: *Gutshop '81: Fish Food Habits and Studies*. Cailliet, G.M. And Simenstad, C.A. (eds.) Academic Press, San Diego. p. 601-635.

Bohnsack, J.A. 1990. The Potential of Marine Fishery Reserves for Reef Fish Management in the U.S. Southern Atlantic. NOAA Technical Memorandum NMFS-SEFC-261. Miami.

Carr, M.H. and D.C. Reed. 1993. "Conceptual Issues Relevant to Marine Harvest Refuges: Examples From Temperate Reef Fishes." *Canadian Journal of Fisheries and Aquatic Sciences*, V49, forthcoming.

Chapman, Duane. 1993. "Environment, Income, and Development in Southern Africa: An Analysis of the Interaction of Environmental and Macro Economics." MUCIA Environmental and Natural Resource Policy and Training Working Paper No. 7. Madison, WI.

Clark, Colin. 1991. "Economic Biases against Sustainable Development." in *Ecological Economics: the Science and Management of Sustainability*. Robert Costanza (ed). Columbia University Press, New York.

Clark, J.R., B. Causey and J.A. Bohnsack. 1989. "Benefits From Coral Reef Protection: Looe Key Reef, Florida." In: *Coastal Zone '89: Proceedings of the Sixth Symposium on Coastal and Ocean Management*, Charleston 11-14 July 1989.

Magoon, O.T., H. Converse, D. Miner, L.T. Tobin and D. Clark (eds.). American Society of Civil Engineers, New York. p. 3076-3086.

Cunningham, Stephen. 1983. "The Increasing Importance of Economics in Fisheries Regulation." *Journal of Agricultural Economics*. 34: 69-78.

Davis, Gary E. 1989. "Designated Harvest Refugia: The Next Stage of Marine Fishery Management in California." *CalCOFI Rep.* 30: 53-57.

DeMartini, Edward E. 1993. "Modeling the Potential of Fishery Reserves for Managing Coral Reef Fishes". U.S. Fisheries Bulletin. Washington D.C., forthcoming.

Goodyear, C. Phillip. 1992. Red Snapper in U.S. Waters of the Gulf of Mexico. Southeast Fisheries Center Miami Laboratory. Miami FL.

Kuhn, H.W. and A.W. Tucker, 1951. "Nonlinear Programming," in J. Neyman (ed.),

Proceedings of the Second Berkely Symposium on Mathematical Statistics and Probability. University of California Press, Berkeley.

Leslie, P.H. 1948. "Some Further Notes on the Use of Matrices in Population Mathematics." *Biometrika* 21:1-18.

New England Fisheries Management Council (NEFMC) 1996. Final Amendment #7 to the Northeast Multispecies Fishery Management Plan, Volume 7, February 7, 1996.

Polacheck, Tom. 1990. "Year Around Closed Areas As A Management Tool." *Natural Resource Modeling*. 4(3): 327-353.

Roberts, Callum and Nicholas Polunin. 1991. "Are Marine Reserves effective in Management of Reef Fisheries." *Reviews in Fish Biology and Fisheries*. 1: 65-91.

Roberts, Callum and Nicholas Polunin. 1993. "Marine Reserves: Simple Solutions to Managing Complex Fisheries." *Ambio*, 22(6): 363-368.

Rowley, R.J. 1994. "Case Studies and Reviews: Marine Reserves in Fisheries Management." *Aquatic Conservation: Marine and Freshwater Ecosystems*, 4: 233-254.

Trippel, Edward A. 1995. "Age at Maturity as a Stress Indicator in Fisheries." *BioScience*, 45(11):759-771.

Appendix: Model of a marine reserve

In this section I present a multiple cohort fisheries model with reserve size as the choice variable. The model, through a stock recruitment relationship 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.

Age structure of the population in the fishery is described using modified Leslie (1948) population matrices⁹[14]:

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

where:

$X(t)$ and $Y(t)$ are $1 \times n$ row vectors of the numbers of fish of age a at time t in the fishery and reserve respectively,

$Z^x(t)$ and $Z^y(t)$ 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 $T^{xy}(t-1)$ and $T^{yx}(t-1)$ 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,

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

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

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

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 $t-1$,

$\tau_{xy}(t)$ 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 $R^{xy}(a,t-1)$,

$R^{yy}(a,t-1)$, $\tau_{xy}(t)$, and $zy(a,t-1)$.

Recruitment is a function of overall (fishery and reserve) egg production and biomass density in the area of settlement (fishery or reserve). The recruitment coefficients are specified as:

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

where:

$B(D^x(t))$ is the density dependent recruitment rate for the fishery,

$D^x(t)$ 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 return¹⁰[15]. The fishery and reserve receive proportions $1-S$ and S , respectively, of recruits. If recruitment is purely local, then the only interaction between the reserve and fishery will be through emigration and immigration¹¹[16]. Fecundity is assumed to increase more rapidly than size of fish. A larger reserve size increases average population age and size, and thus larval export increases proportionally faster than reserve size.

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):

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

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 density¹²[17].

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, fishing

mortality and emigration. The conditional probability of surviving in the fishery and the reserve from age $a-1$ to age a can be decomposed into:

$$\begin{aligned} z^x(a-1, t-1) &= 1 - M^x(a-1) - \left(\frac{D^x(t-1)}{D^y(t-1)} \right) \tau^{xy} - F^x(a-1) \frac{E}{1-S}; \\ z^y(a-1, t-1) &= 1 - M^y(a-1) - \left(\frac{D^x(t-1)}{D^y(t-1)} \right) \tau^{yx} - F^y(a-1) \frac{E}{1-S}, \end{aligned} \quad (4')$$

where:

E is the predetermined effort level¹³[18] ,

$F^x(a-1)$ 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 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 I 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 emigration rate from the fishery to the reserve is and the higher the emigration rate from the reserve to the fishery is¹⁴[19].

Fishing mortality equals the fishery or reserve age specific mortality rate multiplied by intensity of effort divided by the size of the fishery (proportion of the pre-reserve fishery open to fishing). This implies that total effort remains constant, and all effort displaced by the introduction of a reserve is transferred to the open fishing area. Due to the reduction in the area open to fishing, the intensity of effort increases¹⁵[20].

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

where

$$NPV = \text{MAX}_S \sum_{i=0}^{\text{infinity}} \left(\frac{1}{1+i} \right)^i P[W^x(t) F^x X(t) + W^y(t) F^y Y(t)] \bullet \left(\frac{E}{1-S} \right) \quad (5')$$

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.

If $S = 1$, then the entire area is closed to fishing and harvest is illegal. If no reserve is optimal, then $S = 0$. That is,

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

The optimal reserve size depends on the initial stocks and age class structure of the fishery and reserve. For simplicity I 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: where:

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

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). Since the choice variable S is assumed to be time invariant, we can use static rather than dynamic methods to determine the optimal reserve size.

16^[a]¹ Dick Brazee aided in formalizing the analytical model. Dick Brazee, Peter Bailey, John Braden, Bruce Hannon and Hayri Onal offered helpful comments on previous drafts. Support from the Department of Agricultural Economics, University of Illinois Urbana-Champaign, where I completed most of this research, is gratefully acknowledged.

¹⁷^[b] All values in the table are a percentage of the maximum value achievable with no reserve, roughly the maximum sustainable yield.

¹⁸^[c] Minimum harvest occurs when the reserve is first imposed.

¹⁹^[d] Harvests recover to near new equilibrium levels within 6 to 8 years, though stabilization at the new equilibrium takes longer.

²⁰^[e] Equilibrium was reached by year 60 in all cases. A discount rate of 5% is used throughout.

21[f]Assumes starting population approximately equal to 25% of the fishery at the 2.0 effort level with no reserve.

Xii[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.

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

xivXV[3]XviExtensive, 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).

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

XXiii[5]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.

Xix[6]Spawning Stock Biomass (SSB) does increase. However, without a stock recruitment relationship, this does not impact future recruitment.

XX[7]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).

XXi[8]Recruitment is deterministic. Stochastic recruitment makes interpretation of simulation results too difficult.

XXii[9]STELLATM is an icon based programming package developed by High Performance Systems.

XXiii[10]In the grid search procedure, I first simulated NPV from equation (5) under several reserve sizes subject to (1), (6) and (7). I then decreased the step size in the range of reserve sizes that had the maximum NPV. I repeated the process until the optimal reserve size was reached. I used this procedure rather than simulating (9) subject to (1), (6) and (7) because it avoided potential convergence problems and was much faster.

XXiv[11]An alternative to limiting reserve size is to gradually increase the reserve size over time to ensure a minimum harvest level is maintained.

XXV[12]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.

XXvi[13]This implies that resource limitations or crowding either do not occur or do not affect fish behavior or growth.

XXvii[14]For simplicity I 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).

XXViii[15]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.

XXIX[16]Local recruitment is implied in Polacheck (1990).

XXX[17]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.

XXXi[18]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.

XXXii[19]Using density independent emigration is a simpler alternative. In the simulation when I replaced only density dependent emigration with density dependent emigration the changes in the results were small. When density independent emigration is combined with density independent growth, then optimal reserve sizes and NPV of harvests increase significantly.

XXXiii[20]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).
