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**"Managing Artisanal Fisheries  
with Marine Fishery Reserves:  
An Alternative to Managing  
Catch or Effort"**

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**Supplementary Paper No. 3**

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# Foreword

This "Supplementary Paper" is a product of the Environmental and Natural Resources Policy and Training (EPAT) project funded by the United States Agency for International Development (USAID). EPAT is part of USAID's effort to provide environmental policy information to policymakers and practitioners in developing countries. The objective is to encourage the adoption of economic policies that promote sustainable use of natural resources and enhance environmental quality.

EPAT "Supplementary Papers" are intended to augment the EPAT publication series. They typically focus on technical aspects or contain extensive details on a topic of interest to a particular segment of the EPAT audience. They may also assist development professionals, civil servants, project officers, and researchers who are directly involved in the implementation of development activities.

This "Supplementary Paper" deals with the problem of decreasing production of artisanal fisheries. These fisheries are near shore, used by small-scale fishers, and employ primarily labor-intensive methods. This paper reviews the use of marine reserves to control the decreasing production of artisanal fisheries. Marine reserves also protect the habitat and preserve marine biological diversity. Since artisanal fishers produce nearly one-third of the worldwide harvest of food fish, policymakers need to know about alternative approaches available to both sustain this catch and protect the marine environment.

USAID has supported part of the preparation costs of this paper and the nominal costs of duplication and mailing in response to requests from interested EPAT readers. The total amount is estimated to be \$9,000. The availability of the paper is being announced to more than 2,000 policymakers and professionals in developing countries. We will assess its effectiveness by soliciting the views of recipients. An evaluation sheet is enclosed with each mailing of EPAT/MUCIA publications for that purpose.



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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 efficient nor desirable for artisanal fisheries in developing countries. We need new management strategies for artisanal fisheries. Artisanal fisheries are primarily those near to the shore used by small-scale fishers using labor-intensive methods with little or no modern technology.

Artisanal fishers catch nearly one third of the food fish harvested worldwide. Yields in many artisanal fisheries have dropped dramatically. Marine fishery reserves may be a possible and effective alternative management strategy for inshore artisanal fisheries.

In the appendix, this paper includes a simulation of a dynamic model of marine fishery reserves applicable to artisanal reef fisheries. In contrast with previous models, it is fully dynamic and provides information on both equilibrium conditions and the path to equilibrium. The model incorporates a stock recruitment relationship which accounts for changing fertility of the fish population. The simulation results suggest that marine reserves can sustain or increase yields for moderate to heavily-fished reef fisheries but will probably not improve yields for lightly-fished fisheries.

# Glossary

<b>Artisanal Fishery</b>	<b>Artisanal fisheries are those that are exploited by small-scale fishers using labor intensive methods with little or no modern technology. Typically these fishers use multiple technologies and target multiple species. This group also includes part-time, subsistence, and small-scale commercial fishers.</b>
<b>Biomass</b>	<b>Biomass refers to the total weight of living organisms in a given area. It may refer to only a subset of an organism such as one species or to several species.</b>
<b>Cohort</b>	<b>Cohorts makeup an age class of fish recruited to the fishery at the same time.</b>
<b>Inshore Fisheries</b>	<b>These are marine fisheries in shallow waters close to coastlines including reefs, lagoons, mangrove swamps, and estuaries.</b>
<b>Marine Fishery Reserves</b>	<b>Reserve implies loss of legal rights in many contexts.</b>
<b>MAY</b>	<b>Maximum Annual Yield</b>
<b>MSY</b>	<b>Maximum Sustainable Yield</b>
<b>Multispecific Fisheries</b>	<b>These are fisheries in which the same group of fishers target multiple species.</b>
<b>NPV</b>	<b>Net Present Value</b>
<b>Recruitment</b>	<b>Recruitment refers to the entrance of immature fish into the fishery when they reach fishable size. This is a function of the number of larvae introduced as well as their survival rate as immature fish.</b>
<b>Stock-recruitment Relationship</b>	<b>A stock recruitment relationship refers to the rate and spatial pattern of recruitment as a function of the population structure, size, and location of the adult population of the fishery.</b>
<b>STELLA</b>	<b>A trademarked, high-level, computer programming language that solves sets of simultaneous difference equations.</b>

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# **Introduction**

## **The Need for Regulation of Artisanal Fisheries**

Artisanal fishers catch nearly one third of the food fish harvested worldwide, mostly from inshore fisheries (see figure 1). In Asia, artisanal fishers provide two-thirds of the total catch, and, in Africa, they account for five-sixths of the total (Bailey 1988). Of the approximately 15 million people directly employed in the fisheries sector in developing nations, more than 90% are artisanal fishers. An equal number of people find employment indirectly in such support services as processing, marketing, boat building, and transportation (Bailey, Cycon, and Morris 1986).

Despite the importance of artisanal fisheries in providing food, income, and jobs, they are very rarely regulated. In many artisanal fisheries, the need for regulation has become acute. Yields have dropped dramatically as increased pressure has been put on these fisheries. Favorite target species such as large predator fishes, lobster, conch, and giant clams often disappear completely. The reasons for the decrease in yields vary. Human populations have grown, power and sophistication of fishing technology has increased, and large scale commercial fishing and shrimping operations have encroached on inshore areas previously left to artisanal fishers. In addition, decentralized traditional systems of fisheries management such as lagoon and sea tenure, closed seasons, and closed areas have broken down as areas have become more "developed" (Johannes 1978).

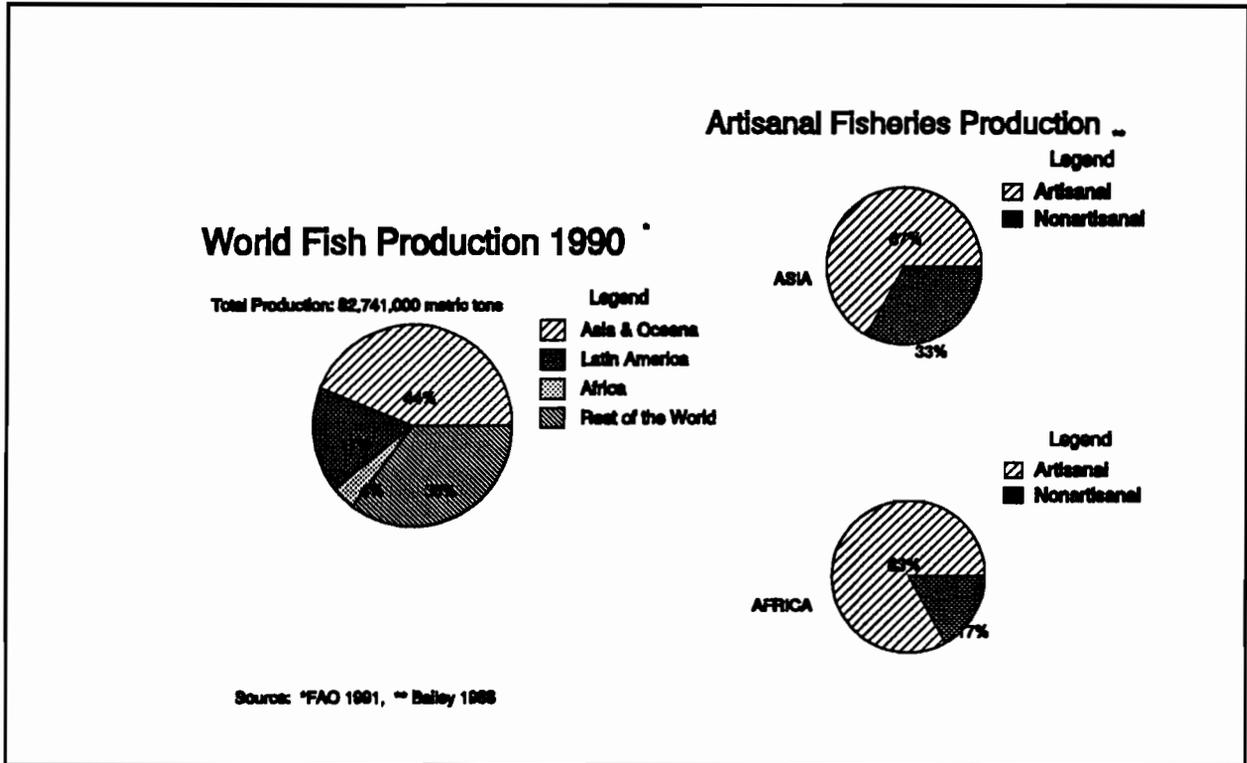
In some cases, technical expertise and funding necessary to efficiently manage fisheries and protect marine resources is lacking. In other cases, the government<sup>1</sup> does not consider the problem important or there is political opposition to change. Almost always, the physical and economic nature of fisheries is sufficiently complex to make solutions difficult. Regulation and management systems that work for modern commercial fisheries are usually not suitable for artisanal fisheries. We need alternative methods to deal with the special problems presented by these fisheries.

## **Marine Fishery Reserves as a Management Alternative**

One alternative is to set aside reserves closed to fishing. These reserves will add to the surrounding fishery and may protect it against collapse. However, there has been very little experimental research on the usefulness of reserves for sustaining or improving fishery yields. There has been some simulation work, but it leaves many questions unanswered. Present models yield information only on the long-run equilibrium and do not incorporate stock-recruitment relationships that may be the primary benefit of reserves.

**Figure 1. Fish Production in Developing Countries**

Fishers harvest almost two-thirds of the world's fish catch from the waters of developing countries. Of that amount, artisanal fishers catch a large fraction, two-thirds of the catch in Asia and five-sixths in Africa.



In the appendix, we have developed a dynamic model of marine reserves applicable to many of the target species found in inshore fisheries and fished by artisanal fishers. In contrast with previous models, this model is fully dynamic and provides information on both equilibrium conditions and the path to equilibrium. The path to equilibrium is important because the full impact of the reserve may not be visible for several years. The model incorporates a stock recruitment relationship that accounts for changing fertility of the fish population. We categorize fish separately by age class and location, either inside

or outside the reserve. This separation allows differentiated behavior, depending on location and age class, which can have important effects on the results of the model. These effects were not addressed by previous yield per recruit analyses.

Although the model is a simplified description of adding a reserve to a previously fully-open fishery, clear qualitative results are scarce. To address this lack of qualitative results, we present a simulation based on red snapper data from the Gulf of Mexico. The simulation provides further insight into the impacts of different size reserves under varying conditions. It also illustrates the impacts on the fishery when key biological assumptions vary.

# **Problems and Alternatives for Management of Artisanal Fisheries**

## **Problems with Conventional Regulatory Methods**

Common methods for regulating commercial fisheries include: licenses, catch quotas, gear restrictions, and closed seasons. These practices try to restrict catch by limiting either the quantity or efficiency of fishing effort. For several reasons, these practices are neither efficient nor effective for managing artisanal fisheries. Usually in artisanal fisheries there are numerous fishers, each accounting for a very small fraction of total catch. Many are only part-time fishers and do not sell much of the catch in formal markets. This combination of characteristics makes the administration and enforcement of conventional regulatory methods extremely difficult and expensive. Furthermore, closed seasons can cause severe hardship for fishers who rely on the fishery for subsistence or have no other opportunities for employment.

Also, artisanal fisheries use a wide variety of fishing technologies and methods and harvest several different species. Roberts and Polunin (1991) note that conventional fisheries' management methods are based on single-species population dynamics and are unsuitable for multispecific fisheries. Controlling fishing effort becomes extremely complicated when fishers use multiple methods and technologies to harvest multiple species.

## **Decentralized Regulatory Strategies**

Conventional regulatory systems for commercial fisheries are of limited use in many inshore artisanal fisheries. However, these fisheries often have certain characteristics that accommodate other "non-conventional" methods of regulation. Their closeness to shore makes decentralized regulation possible and efficient if appropriate institutions are in place. These regulatory systems usually transform open access fisheries into common property or private property. It is necessary to exclude fishers who do not have fishing rights, and excluding fishers is considerably easier when the fishing ground is close to shore. Furthermore, because it is homogeneous population groups who exploit inshore artisanal fisheries it is easier to seek cooperation on resource exploitation.

Decentralized regulatory systems of this type, historical and current, include formal or informal tenure of marine areas by groups. In some cases, the tenure for a portion of a reef, coastal area, or lagoon is ceded by the government to a municipality, village, clan, family, or even an individual. Examples include municipal sea tenure in the Philippines and Indonesia (Cycon 1986, Emmerson 1980), designation of fishing rights to particular lagoons to fishing cooperatives in Mexico (Ostrum 1990), and family and clan tenure of reef and lagoon areas in Oceania (Johannes 1978).

Daily or seasonal tenure can also control fishing in some cases. A fishing cooperative in Turkey used a system of rotating rights to specific fishing spots to limit fishing in productive areas (Ostrum 1990). In the Dutch Antilles, a fisher can acquire rights to a shoal for an entire season by staking a net, even if the net is later moved by the fisher (Ostrum 1990). Other systems include decentralized, locally-adapted versions of the "orthodox" methods such as limits to entry, gear restrictions, and closed seasons.

Though these systems offer alternatives to orthodox regulatory methods, they have problems. Most of these regulatory systems, particularly informal ones, require a high degree of cooperation among fishers. This often breaks down as development disturbs homogeneous traditional cultures or population growth increases pressure on fisheries (Johannes 1978). While these methods of regulation may limit fishing, they may still result in overfishing, particularly if they do not adjust to changes in stock due to natural conditions.

## **The Advantages of Regulating Reef Fisheries With Reserves**

Recently, several fisheries biologists (Roberts and Polunin 1991, Bohnsack 1990, Davis 1989, Carr and Reed 1993) suggested that, sometimes, marine reserves may be an appropriate tool for sustaining or increasing harvests from certain fisheries. Closing part of the fishery to fishing may yield net increases to overall fishery harvest by setting aside a stocking area that encourages reproduction and growth.

Marine reserves may be particularly valuable in overcoming the difficulties of managing artisanal fisheries. Reserves simplify the task of regulation. With reserves, it is not necessary to keep track of stocks and adjust effort levels for all different species. Management requires much less information than methods that try to control stock size through restricting catch or effort. Reserves also may provide insurance against fishery collapse from management failure. Reserves do not require close monitoring and effective enforcement of harvest and effort. Enforcement only requires keeping fishers out of the reserve.

However, we should not underestimate the difficulties of enforcement. If local fishers do not support the reserve, enforcement may be difficult and expensive. Fishers have blocked establishment of reserves that they felt did not benefit them (Valdes-Pizzini 1990). Even if a government creates a reserve on paper, there may be a lack of local political support or limited resources for enforcement. Fishers began fishing a reserve at Sumilon Island in the Philippines when voters elected a new local government that did not support the reserve (Alcala 1988). Systems of governance which are both economical and politically feasible are a critical part of reserve design.

Reserves created for fisheries management have additional benefits including protection of biodiversity and areas of undisturbed habitat for scientific study. They can also create sightseeing areas that can increase tourist income.

# **Research on Marine Fishery Reserves**

## **When, Where, and How Marine Fishery Reserves Will be Effective**

To date, the purpose of marine reserves has been primarily to conserve marine habitat and organisms within the reserves. A key question is whether marine reserves will be effective for sustaining or improving yields of artisanal or other fisheries. Reserves will likely only be effective in sustaining or increasing yields of certain types of fisheries. They are probably not appropriate for management of highly mobile or migratory species. Reserves are likely to be effective for inshore fisheries. Examples are those based on reefs or mangrove swamps where the reserve can protect many important target species of fish and shellfish that are non-migratory.

The potential for marine reserves as a fisheries management tool appears to be greatest for fisheries based on tropical reefs where most research on reserves has already focused. Coral reefs are potentially some of the most productive marine habitats in the world. If properly managed, they could supply 12% of world fish production and more than 20% of fish production in developing countries. However, reefs and nonreef coral communities within 15 kilometers of shore are poorly managed and usually overfished (McManus 1988).

The behavior characteristics and population dynamics of most reef species suggest that reserves could be an effective management tool. Adults of most reef species usually stay within a limited geographical area. However, eggs and larvae of many reef species spend several weeks or even months on the open ocean before developing into juvenile fish and returning to the reef. The larvae from a portion of a reef fishery usually disperse widely throughout the fishery. In this way, a protected population can replenish the stocks of surrounding areas with recruits.

Many fisheries are subjected to growth overfishing but not recruitment overfishing. Growth overfishing reduces the average size of the individual fish below that which results in a maximum annual growth rate of fish biomass. Recruitment overfishing reduces the population fertility to the point that the fishery does not have enough recruits. Reef fisheries often do not have enough recruits, especially of heavily-fished species. A reserve would allow an older, larger and more fertile<sup>2</sup> population to develop, which, by increasing recruitment, may more than compensate for fishing area lost to the reserve.

## **Protecting Life and Habitat Inside Marine Fishery Reserves**

To date, research on reserves has focused mainly on their ability to protect life and habitat within the reserves. Roberts and Polunin (1993) undertook an extensive study of marine fisheries on the Sinai coast of Egypt. They studied nine sites between Ras Mohammed and Dahab, including heavily-fished

and lightly-fished areas. They also included "unfished" areas within the Ras Mohammed National Marine Park. The purpose of this study was to examine how the level of fishing affected fish densities and size for a variety of species.

The study reports that effects on fish abundance in protected areas are varied and complex. Some species were more abundant on unfished sites than fished sites; however, others were more abundant in fished areas (Roberts and Polunin 1993). In general, however, the larger predator species, often preferred targets, were more abundant and larger in unfished areas.

Two studies of reserves in the Florida Keys of the United States show the effects on fish population inside a reserve that banned spear fishing. Bohnsack (1982) found higher densities and larger sizes of several species in the Key Largo National Marine Sanctuary than on reefs close by which allowed spearfishing. At the time of the study, there had been no spearfishing inside the reserve for 20 years. The differences were greatest for snapper and grunts, favored by spearfishers. Two years after a spearfishing ban, a survey of Looe Key reef showed a 93% increase in snappers and 439% in grunts (Clark, Causey and Bohnsack 1989). They also found other species that had not been present before the ban.

Even though there was a commercial fishing ban in the Key Largo and Looe Key reserves, recreational spearfishing had been enough to deplete populations of some species. This shows the extreme vulnerability to overfishing of some species on tropical reefs.

Roberts and Polunin (1993) looked at fish abundance in the Hol Chan Marine Reserve in Belize and the Saba Marine Park in the Netherlands Antilles. Both had been closed to fishing since 1987, four years before the study. Comparing the reserves with surrounding fished areas, they found significantly higher densities inside the reserve for some species but not for others. However, the frequency of large fish was substantially higher within the reserve. They could not make conclusions about the effects of the reserve on adjacent fish populations because they had not collected data before the reserve was set aside.

The reserves discussed above were all on tropical reefs. The evidence offers strong support for the theory that reserves will allow a more abundant, larger, and more fertile population to develop in protected areas on tropical reefs. Evidence supporting the theory that the reserve population will supplement the fishery surrounding the reserve is much weaker.

## **The Effect of Marine Fishery Reserves on Surrounding Fisheries**

The only clear support for the effectiveness of reserves in improving fishery production is the results of research done on a small reserve in the Central Philippines (Russ 1985, Alcala 1988). A 700-meter-wide section of the 50-hectare fringe reef surrounding Sumilon Island was closed by the government to fishing between 1974 and 1983. The reserve was about 25% of the total reef area. The research team found that yields (t/km<sup>2</sup>/yr) in the non-reserve areas of Sumilon Reef increased from a range of 14 to 23.6 tons between 1977 and 1980 to as high as 36.9 tons in 1983-1984 (Alcala 1988).

The researchers did not estimate yields before establishment of the reserve. However, decreases in yields, after reopening the reserve to fishing, show gains in productivity from the reserve. Because of political changes in 1984, the government withdrew protection of the reserve and fishers began to encroach on the reserve. Between 1983 and 1985, the density of primary target species fell drastically, by 45% for *serranids* (these include grouper) and 95% for *lutjanids* (snapper) (Russ 1985). Catch per unit effort declined by 55% to 33%, depending on the type of gear. And overall yield for the reef declined to 19.87 t/km<sup>2</sup>/yr (Alcala 1988).

Alcala's study suggests that reserves on tropical reefs are effective in increasing production in the surrounding fishery. However, natural fluctuations in recruitment or other factors might also explain these results. We need additional experiments to analyze marine reserves. However, since most of the primary target species on tropical reefs are slow growing and long lived, it requires a minimum of five to 10 years to see the full impact of a reserve. So experimental results will be slow in coming.

## Modelling Marine Fishery Reserves

Modelling and simulation can provide limited answers more quickly and can assist the design of experimental research. Polacheck (1990) used data from cod to investigate the effect of closed areas on yield per recruit (the average harvest weight per fish that reaches fishable size). DeMartini (1993) applied Polacheck's model to three Pacific reef species to study spawning stock biomass (SSB) per recruit (the average cumulative fertility of a fish during its lifetime). The results of the analyses suggest that reserves could be effective in increasing SSB per recruit but would do little to improve yield per recruit.

Polacheck and DeMartini base their analyses on the Beverton and Holt fisheries model that assumes identical cohorts. This model imposes two important limitations:

1. the analyses represent long-run equilibrium results; short-run impacts may be different, and
2. the analysis does not address the effect of the closed area on future recruitment.

Without incorporating changes in recruitment, the Beverton and Holt model cannot predict the long-term effect of a permanently-closed area if changes in recruitment are significant. To address this question, we need a model incorporating a spatial stock-recruitment relationship (Polacheck 1990).

If recruitment limits reef fisheries, but the protected population in the reserve will provide recruits to the surrounding fishery, then a stock-recruitment relationship is fundamental to evaluating the performance of reserves.

Since it will take several years to see results from a marine reserve and the short-run impacts may be very different than long-run impacts, a dynamic analysis of the short run is important. Fishery harvests may fall initially and may take several years, if ever, to reach a steady state equilibrium. An examination of the path before reaching the steady state is critical to evaluating reserve performance.

We must weigh early losses against future gains. For many fisheries, it is important to consider the minimum level to which production will drop in early stages as the fishery may be a critical source of nutrition and employment. If opening a reserve reduces fishing effort, there may be another cost in the form of the opportunity cost of capital that remains idle.

## Simulation Results

We developed a simulation model (Appendix) that provides insight into the impacts of reserves on fishery population and harvest. The simulation illustrates the impact on fishery production and optimum reserve size of varying several key parameters including: effort levels, recruitment, emigration rates, and growth rates. Because of the uncertainties surrounding many of the biological parameters, we do not expect the simulation results to yield accurate quantitative data on the impacts of reserves. The purpose of the simulation is to illustrate the economic ramifications of a range of commonly-held biological assumptions. We model the simulation using STELLA™<sup>7</sup> a dynamic differential equation solver. The simulation procedure begins with a steady state population structure corresponding to a particular level of fishing effort and no reserve. We then impose a reserve, closing a fraction of the area of the fishery. We simulate population and fishery dynamics until we reach a new steady state.

### Optimal Reserve Size and Fishery Production and Effort Intensity

Optimal reserve sizes vary greatly with assumptions about fishing effort. Table 1 shows optimal reserve sizes and production levels at a variety of effort levels for the increased intensity model. Table 2 shows results for the fixed intensity model. The rows labeled "min harvest" show the minimum level to which annual production falls. "Annual harvest" reflects annual yields in year 60. The rows labeled "NPV harvest"<sup>8</sup> show cumulative yield up to year 60 discounted back to period one value. All simulation runs reached a new equilibrium steady-state by year 60. Rows of the tables show the results of different levels and responses of effort. Columns show the results of various reserve sizes including the MAY and dynamic optima.

From tables 1 and 2, it is clear that at low fishing intensities, marine reserves provide no benefit to fishery production. At low fishing intensities, reserves can dramatically reduce fishery production both in the short run and long run. At the MSY level (.75) of effort, production drops by nearly 20% with a reserve covering 20% of the total fishery.

As the level of fishing effort rises, optimum reserve size rises. The highest absolute levels of fishery production come at a moderate level of effort (effort=1.0) and relatively small (5% of total area) reserves (see figure 2). However annual fishery production rises by less than 4% over the no-reserve MSY level. And in no case is the discounted cumulative production higher than the MSY level.

When fishing effort is moderate or high, reserves result in significant increases in fishery production compared with the absence of regulation. At high fishing intensities (such as the 2.0 or 2.5 effort level range), reserves increase annual and discounted cumulative fishery output by more than 10%. At these fishing intensities, optimal reserve size ranges from 15 to 30% of the total fishery area.

At the 1.5 effort level and above, optimal reserve size is larger for the increased-intensity cases than for the fixed-intensity cases. The explanation for this is that at high fishing intensities the increased fishing offsets some of the losses from closing a portion of the fishery. When fishing intensity is high, the fishery population is sparse which causes the recruitment rate to be high. The increased recruitment that results from expansion of the reserve outweighs the growth overfishing that results from increased intensity of effort.

## **Steady State and Dynamic Optima**

With the beginning of a reserve, fishery production initially falls and takes several years to achieve a steady state. Under the dynamic optimum, these early losses outweigh future gains, which reduces the discounted value of reserves and decreases the optimal size of reserves. In all cases, the optimal reserve size for the dynamic optima is smaller than or equal to the reserve size for the MAY. The optimal reserve size also varies with the magnitude of the discount rate.

In the initial simulations, we used a discount rate of .10. Significant differences between the static and dynamic optimum sizes occurred in many cases (see tables 1 and 2). At low discount rates, the MAY and Dynamic optima differ little; however, they differ dramatically if we raise the discount rate to 20% (see table 3). A rate of .10 is high by developed-country standards; however, discount rates of poor in developing countries tend to be high (Ciriacy-Wantrup 1963, Clark 1991, Perrings 1989). Thus rates of .10, .20 or higher may be appropriate for artisanal fishers who typically have relatively low incomes. Many people argue, however, that we should use very low discount rates to ensure preservation of resources for future generations.

## **Sensitivity to Economic and Biological Assumptions**

### **Economic Assumptions**

Elasticity of fish prices will affect the usefulness of reserves. If fish prices are elastic, it will reduce both gains from increased production and early losses (to income if not to nutritional needs of the population). The impact on optimal reserve size depends on the demand function.

Cost of fishing effort also affects the performance of reserves. The fixed-intensity model implies a reduction in effort. If costs of effort are high, this would improve the performance of the reserve. The increased-intensity model implies no change in effort or costs. In the extreme case, total effort may increase so much that any economic gain will be lost. Enforcement costs also will decrease the value of reserves. Marine reserves may provide other benefits such as the amenity and existence value (Norton 1988) of biodiversity and habitat protected by the reserve. This may increase optimal reserve size or make reserves viable even without enhancing fishery production.

**Table 1. Fishery Performance with Increased Intensity Effort at Varied Base Effort Levels**

Reserve Size (S) Effort Level (E)	S=0	S=.1	S=.2	S=.3	Maximum Annual Yield (MAY)	Optimal NPV of Harvest (Dynamic Optima)
<b>E=.75/(1-S)</b>					<b>S=0</b>	<b>S=0</b>
min harvest	1000	936	867	792	1000	1000
annual steady-state harvest	1000	975	936	891	1000	1000
NPV cumulative harvest	1000	972	933	886	1000	1000
<b>E=1.0/(1-S)</b>					<b>S=.05</b>	<b>S=0</b>
min harvest	968	919	865	806	944	968
annual steady-state harvest	968	970	941	895	975	968
NPV cumulative harvest	968	952	922	879	962	968
<b>E=1.5/(1-S)</b>					<b>S=.18</b>	<b>S=.13</b>
min harvest	892	838	780	717	792	734
annual steady-state harvest	892	934	945	933	946	941
NPV cumulative harvest	892	909	903	880	907	911
<b>E=2.0/(1-S)</b>					<b>S=.27</b>	<b>S=.17</b>
min harvest	845	788	727	662	682	745
annual steady-state harvest	845	913	949	959	962	945
NPV cumulative harvest	845	883	893	882	891	895

Note: Values are in pounds or dollars assuming a fixed price of \$1/lb. live weight. We use a discount rate of .1 throughout. A value of 1000 corresponds with production at the .75 effort level, roughly the maximum sustainable yield in the absence of a reserve. NPV cumulative harvest is the present value of harvests from imposition of the reserve through year 60.

Source: STELLA Simulation

**Table 2. Fishery Performance with Fixed Intensity Effort at Varied Base Effort Levels**

<b>Reserve Size (S) Effort Level (E)</b>	<b>S=0</b>	<b>S=.1</b>	<b>S=.2</b>	<b>S=.3</b>	<b>Maximum Annual Yield (MAY)</b>	<b>Optimal NPV of Harvest (Dynamic Optima)</b>
<b>E=.75</b>					<b>S=0</b>	<b>S=0</b>
min harvest	1000	885	774	670	1000	1000
annual steady-state harvest	1000	909	814	720	1000	1000
NPV cumulative harvest	1000	910	817	721	1000	1000
<b>E=1.0</b>					<b>S=.06</b>	<b>S=.05</b>
min harvest	968	872	776	681	910	920
annual steady-state harvest	968	1030	959	867	1038	1037
NPV cumulative harvest	968	973	912	827	983	984
<b>E=1.5</b>					<b>S=.15</b>	<b>S=.06</b>
min harvest	892	804	716	628	760	839
annual steady-state harvest	892	930	932	894	943	926
NPV cumulative harvest	892	899	877	831	894	903
<b>E=2.0</b>					<b>S=.19</b>	<b>S=.16</b>
min harvest	845	762	679	596	687	712
annual steady-state harvest	845	922	952	927	952	946
NPV cumulative harvest	845	883	882	846	884	886
<b>E=2.5 *</b>					<b>S=.25</b>	<b>S=.28</b>
annual steady-state harvest	Collapse	901	949	949	961	942
NPV cumulative harvest		557	645	658	658	660

\* Assume starting population of 500,000 fish with a total weight of 334,079 lbs.

Note: Values are in pounds or dollars assuming a fixed price of \$1/lb. live weight. We use a discount rate of .1 throughout. A value of 1000 corresponds with production at the .75 effort level, roughly the maximum sustainable yield in the absence of a reserve. NPV cumulative harvest is the present value of harvests from imposition of the reserve through year 60.

Source: STELLA Simulation

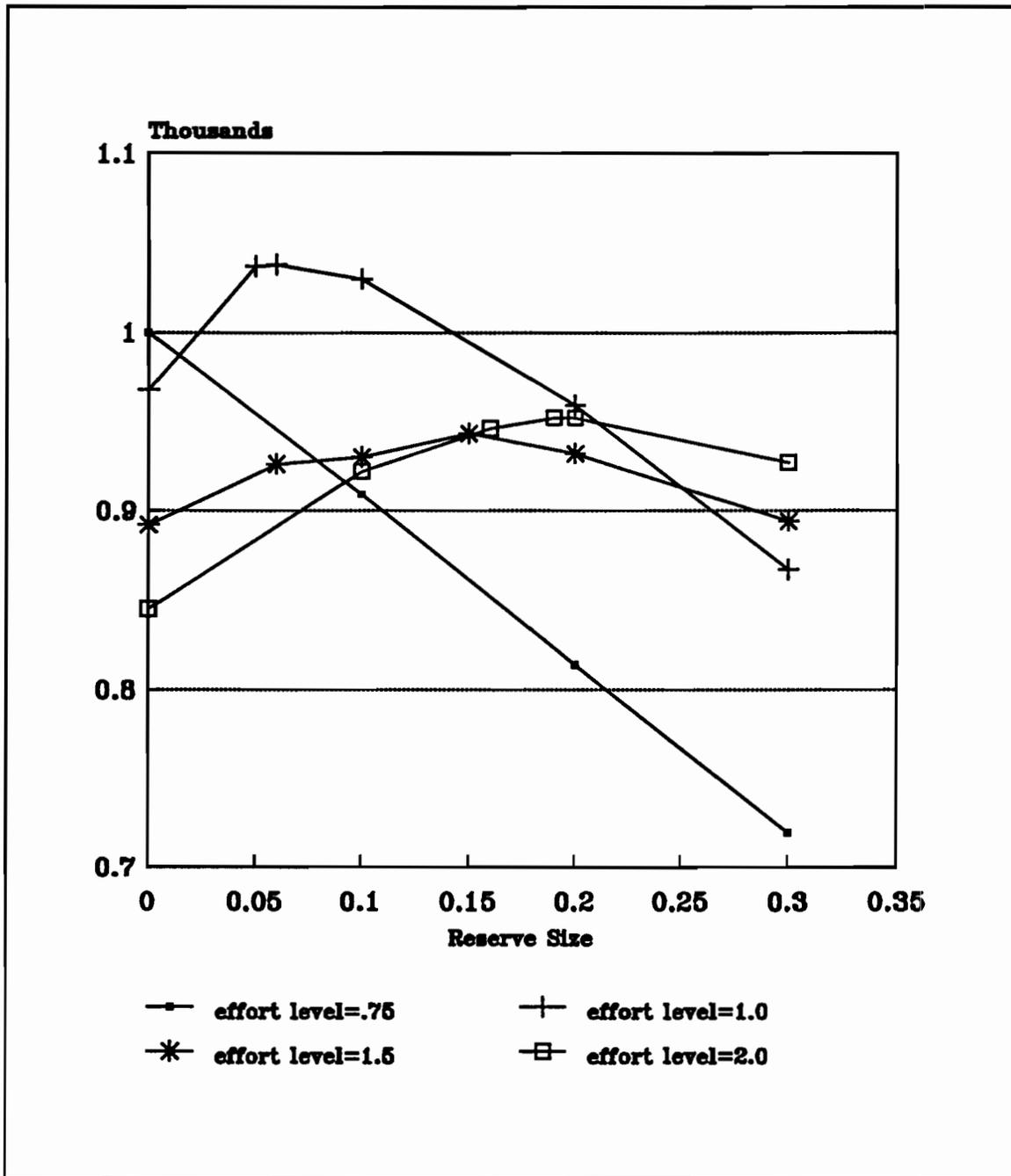
**Table 3. Cumulative Net Present Value of Harvest up to the End of Year 60 with Varied Discount Rates**

<b>Reserve Size (S) Discount Rate (i)</b>	<b>S=0</b>	<b>S=.1</b>	<b>S=.2</b>	<b>S=.3</b>	<b>Optimal NPV of Harvest (Dynamic Optima)</b>
<b>i=0</b> NPV harvest	5058	5239	5221	5005	<b>S=.15</b> 5290
<b>i=.05</b> NPV harvest	1645	1682	1659	1583	<b>S=.14</b> 1687
<b>i=.1</b> NPV harvest	892	899	877	831	<b>S=.06</b> 903
<b>i=.20</b> NPV harvest	473	465	446	418	<b>S=0.0</b> 473

Note: Effort level is fixed at 1.5. NPV cumulative harvest is the present value of harvests from imposition of the reserve through year 60.

Source: STELLA Simulation

Figure 2. Annual Fishery Production at Year 60 with Varying Reserve Size and Effort Levels



Source: STELLA Simulation

## Biological Assumptions

The simulation results are sensitive to several of the biological assumptions. Unfortunately, the population dynamics of reef fisheries are not well understood. To illustrate the effects of this uncertainty on the effectiveness of reserves, we vary three elements. We change the assumptions of the stock recruitment relationship, the base transfer rates (annual rates of emigration and immigration between the reserve and nonreserve), and the response of growth and transfer rates to increased biomass density.

A key assumption of the model and simulation is the connection between egg production, dispersal, and recruitment. The geographical spread of larvae and later recruitment is not well understood. It is clear, however, that, if there is local distribution of larva and recruitment, it will be better to have many small reserves instead of one large one. In the initial simulations, we assume that larvae mix uniformly throughout the reserve and fishery. With at least some spatial mixing of recruitment across the fishery, results of this model may not be greatly affected by the actual geographical spread of recruits. Only total reserve area as a fraction of the total closed system fishery is important. We treat individual reserves of various sizes, numbers, and locations identically. Less mixing of recruitment geographically would require more, smaller reserves but would not necessarily affect the total area of the reserve as a percentage of the total fishery.

In later simulations, we replaced the assumption of uniform dispersal with local recruitment (i.e. the reserve population provides recruits only for the reserve and the fishery for only the fishery) to determine its impact. This is equivalent to replacing the elements of the first row of the  $T^y$  and  $T^x$  matrices in (1) with zeros. Table 4 shows the results of the local recruitment simulations under a range of base transfer rates at an effort level of 1.5.

Local recruitment decreases the value of the reserves significantly at low transfer rates. Reserves are not effective in improving discounted cumulative yield even with high transfer rates. With a transfer rate of .05, the reserve improves steady state annual production very little and by only about 2% with a higher transfer rate of .1. However, a transfer rate of .4 increases annual production by nearly 12%.

These results contrast with previous results to date (Polacheck 1990, DeMartini 1993) which show reserves to be ineffective at improving yields even with high rates of transfer. The difference results primarily from the incorporation of a stock recruitment relationship. Even at high transfer rates, the reserve tends toward an older and more fertile population, and recruitment to the reserve is subsequently high. The high emigration rates then allow transfer of many of these recruits, as well as older fish, to the fishery, thereby improving production.

Assumptions about the response of growth rates to changes in localized biomass density of the fishery also impact the results of the model. The initial simulations allowed growth and transfer rates to vary with biomass density. Under density-dependent growth, fish weight in the fishery (reserve) depends on the densities of the fishery (reserve) over the life of each class. Density-dependent growth reduces the value of the reserve through decreasing growth of fish in the relatively crowded reserve. Density-dependent transfer also slows the growth of the reserve stock by increasing emigration from the reserve to the fishery.

Later simulations with an effort level of 1.5 relaxed the assumptions of density effects on both growth and transfer; we made growth and transfer density-independent. We replaced the transfer vectors  $T^y(t)$  and  $T^x(t)$  by the vector of constants,  $T^y$  and  $T^x$ . This would imply that resource limitation or crowding either do not occur or do not affect fish behavior or growth. Optimal reserve sizes and production 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 includes both density-dependent growth and transfer.

The rate of transfer and its sensitivity to relative densities also affect the results of the model significantly. Increasing transfer rates increased the MAY optimal reserve size significantly, and, somewhat surprisingly, also increased annual fishery production. The increase in annual fishery production occurred because more large fish enter the fishery from the reserve and increase fishery harvests. Over the range of transfer rates simulated, the increases in harvest outweighed losses to fertility and later recruitment that result from more large fish being caught. However, the impact on the dynamic optimum reserve size and the NPV of cumulative harvests was small. We also reduced the sensitivity of transfer rates to relative biomass densities. Decreased density dependence of transfer reduced optimal reserve sizes but only slightly.

## **Conclusions and Recommendations for Further Research**

### **Conclusions from Model Results**

Conventional regulatory methods that depend on reducing fishing are expensive and difficult or impossible to apply to artisanal fisheries. Marine reserves provide a possible alternative management strategy and appear to be effective in managing reef fisheries that provide a large portion of the catch taken by artisanal fishers.

Our results 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 about biological parameters. Although the lack of accurate data shows that information about absolute levels of production and reserve sizes is not reliable, qualitative results are clear. The analytical model and simulations also show the advantages of dynamic, multi-cohort modelling relative to previous yield per recruit models.

**Table 4. Fishery Performance with Varied Rates of Transfer ( $\tau$ ), Fixed Intensity Effort, and Local Recruitment**

<b>Reserve Size (S)</b> <b>Transfer Rate (<math>\tau</math>)</b>	<b>S=0</b>	<b>S=.1</b>	<b>S=.2</b>	<b>S=.3</b>	<b>Maximum Annual Yield (MAY)</b>	<b>Optimal NPV of Harvest (Dynamic Optima)</b>
<b><math>\tau=.05</math></b>					<b>S=.06</b>	<b>S=0.0</b>
min harvest	892	804	716	628	839	892
annual steady-state harvest	892	897	856	802	901	892
NPV cumulative harvest	892	872	825	767	883	892
<b><math>\tau=.10</math></b>					<b>S=.18</b>	<b>S=0.0</b>
min harvest	892	804	716	628	734	892
annual steady-state harvest	892	908	910	890	911	892
NPV cumulative harvest	892	882	860	815	865	892
<b><math>\tau=.20</math></b>					<b>S=.32</b>	<b>S=0.0</b>
min harvest	892	804	716	628	619	892
annual steady-state harvest	892	904	917	938	941	892
NPV cumulative harvest	892	882	867	853	852	892
<b><math>\tau=.40</math></b>					<b>S=.33</b>	<b>S=0.0</b>
min harvest	892	804	716	628	602	
annual steady-state harvest	892	906	912	982	999	892
NPV cumulative harvest	892	885	868	867	892	892
						892

Note: We fixed effort level at 1.5 and a discount rate at .1 throughout.

Source: STELLA Simulation

While we must consider some results highly subject to biological uncertainties, some strong conclusions are:

1. The effects of a reserve and the optimal size will vary with the both the level of effort and the response of effort to implementation of the reserve. Higher effort levels require larger reserves sizes to achieve maximum production. If we expect total effort to remain constant, this will increase intensity of effort and may require yet larger reserves. 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 (local interest 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 also will limit the size of reserves.
3. Biological assumptions heavily influence the likely economic results of instituting a reserve, and the socio-economic assumptions in turn control the biological results. This interdependence requires cooperation between the disciplines not only at the policy level but at the research level. We must answer economic and biological questions simultaneously if research is to be useful to policymakers. The current large-scale experiments should include a socio-economic component. We must not only study the fish but their land-based predator as well.

## **Future Research Needs**

A clearer understanding of the population dynamics of fisheries is critical to the analysis of the effectiveness and optimal design of marine reserves. The most important and least understood aspect is the relationship between fish stocks and recruitment. It is important to find out if increasing the spawning stock biomass will increase recruitment and what spatial pattern of recruitment will occur. Data on the effects of increasing biomass density on recruitment, growth, and emigration/immigration is also important.

The model and simulation presented did not address the absolute size or location of individual reserves. To do so would require a considerably more complex, explicitly-spatial model. However, an explicitly-spatial model could address several important questions and would be a useful extension of this research. A spatial model could include spatial recruitment patterns and directional migration. It could also address cost changes that may occur if reserves are large and some fishers have to travel further to fish.

The concept of gradually phased-in reserves is another useful extension of this research. This would decrease the initial shock to the fishing industry and might reduce fishers' resistance. Rotating reserves are another possibility. However, it is unclear if either of these systems would achieve the desired increases in fishery production. They also pose additional problems that may make them

impractical. Enforcement will be more difficult if reserve boundaries change frequently. The process of approval and siting of a reserve is long and arduous; frequently changing sites or increases in size may meet with resistance at each step.

The experience with the Sumilon Reserve in the Philippines shows the importance of developing community and local political support for a reserve. Local support can substantially reduce the cost of enforcement and improve the effectiveness of reserves, while a lack of support may result in the failure of a reserve. We need to integrate research on institutional arrangements for marine reserves with biological and economic research. Arrangements will certainly differ with location and culture, but research on traditional resource management systems and case studies of successful reserves will improve the success of future reserves.

## **A Larger Role for Marine Fishery Reserves**

Historically, governments have created marine reserves to protect biodiversity, preserve pristine habitat, and attract tourists. Decisions on whether to establish a reserve have compared these benefits with the cost to fisheries in lost harvest. If reserves can protect biodiversity and habitat while simultaneously protecting fishery production, it greatly increases the possibilities of opening them. Further investigation to find more quantitative information about the best design for reserves and to determine if they will be useful to manage selected fisheries should be given high priority.

# Appendix

## A Bioeconomic Model of a Marine Fishery Reserve

In this section, we develop a single species<sup>3</sup> multiple cohort fisheries model with reserve size as the choice variable. The model incorporates the impacts of a reserve on recruitment and harvest both before and after reaching a steady state. Recruitment, emigration, and immigration between the reserve and fishing areas 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, effort, and age specific catchability. The level of fishing effort is predetermined.

### Population Dynamics

We describe the age structure of the population in the fishery using modified Leslie (1948) population matrices:

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

where:

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

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

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

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

where:

$n$  is maximum fish age,

$R^x(k,t-1)$  is number of recruits to the fishery at time  $t$  provided by an age  $k$  fish at time  $t-1$ ,

$\tau^{yx}(t)$  is the emigration rate from the reserve to the fishery at time  $t$ ,

$x(k,t)$  is the number of fish age  $k$  in the fishery at time  $t$ ,

$y(k,t)$  is the number of fish age  $k$  in the reserve at time  $t$ , and

$z^x(k,t-1)$  is the conditional probability of an age  $k$  fish surviving in the fishery from time  $t-1$  to time  $t$  minus emigration to the reserve.

We can describe the population dynamics for the reserve in a similar way by interchanging  $x$ 's and  $y$ 's, and defining  $R^y(k,t-1)$ ,  $\tau^{xy}(t)$ , and  $z^y(k,t-1)$ . Note that  $\tau^{xy}(t)$  is the emigration rate from the fishery to the reserve.

Recruitment is a function of the number of fish in each age class in both the fishery and the reserve. After recruitment, the number of age k fish in the fishery (reserve) at time t depends on the survivorship of age k-1 fish in the fishery (reserve) plus net immigration from the reserve (fishery).

The hazards to survival are natural mortality, fishing mortality, and emigration. The conditional probability of surviving in the fishery and the reserve from age k-1 to age k can be broken down into:

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

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

where:

$D^x(t)$  = the biomass density of the fishery at time t,

$D^y(t)$  = the biomass density of the reserve at time t,

$E$  = predetermined effort level,

$F^x(k)$  = the fishing mortality rate of fish of age k in the fishery,

$F^y(k)$  = the fishing mortality rate of fish of age k in the reserve,

$M^x(k)$  = the natural mortality rate of fish of age k in the fishery,

$M^y(k)$  = the natural mortality rate of fish of age k in the reserve, and

$S$  = reserve size as a percentage of total reserve and fishery area.

Fishing mortality equals the fishery or reserve age specific mortality rate multiplied by intensity of effort divided by the size of the fishery (fraction 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 transfers to the open fishing area. Because of the reduction in the area open to fishing, the intensity of effort increases.

In the simulation, we also present a case in which none of the effort displaced by the introduction of a reserve transfers 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. The reserve was relatively small and total effort for the fishery did not change but was redistributed in the open area.

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.<sup>4</sup> We assume emigration rates are responsive to resource limitations. These limitations are captured by emigration rates that are a function of the ratio of the population biomass densities of the fishery and the reserve. The fishery (reserve) biomass density is the total weight of the fishery (reserve) divided by size of the fishery (reserve):

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

where  $W(t)$  is an  $n \times 1$  row vector of age specific weights at time  $t$ ,  $w(k,t)$ .

We assume growth rates are density dependent. That is, the age of fish as well as the biomass density of the population<sup>5</sup> determine fish weight. Density affects a fish's growth each period, so its weight reflects biomass densities throughout its life.

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:

$$R^x(k,t) = (1 - S) B(D^x(t)) L(w(k,t)); \quad R^y(k,t) = S B(D^y(t)) L(w(k,t)),$$

where  $B(D^x(t))$  and  $B(D^y(t))$  are density dependent recruitment rates and  $L(w(k,t))$  are weight dependent egg/larva production rates.

We assume eggs or larvae will be transported outside the reserve and fishery, mature into juveniles, mix, and be distributed uniformly over the reserve and fishery upon their return as juvenile fish.<sup>6</sup> The fishery and reserve receive their proportion  $1-S$  and  $S$ , respectively, of recruits. If recruitment is purely local, then the only interaction between the reserve and nonreserve will be through emigration and immigration. We assume fertility will increase more rapidly than fish size. In the simulation, fertility increases exponentially with size of fish (reaching a maximum in fish 15-18 years old) according to data on Gulf of Mexico red snapper (Goodyear 1992). A larger reserve size increases average population age and size, and thus larval export increases proportionally faster than reserve size.

## The Goals of Management

Two important benchmark criteria for fisheries management are the maximum sustainable yield (MSY) and maximization of the net present value (NPV) of the time path of harvests (Clark and Munro 1975, Plourde 1970). Under maximum sustainable yield, the goal is to choose the effort level that maximizes the steady state harvest. Under the NPV criterion, the goal is to choose effort levels in every time period that maximize the sum of discounted profits from harvests over a fixed time horizon.

Here, although effort is predetermined and reserve size is the choice variable, we use similar criteria to evaluate performance of reserves. Maximum annual yield (MAY) refers to levels of stock and reserve size that maximize the steady state harvest. The maximum NPV of harvests (Dynamic Optima) refers to the reserve size that maximizes the value of cumulative harvests discounted back to period one.

To find the reserve size that maximizes annual yield, we impose a steady-state on the population dynamics equations. In the steady-state the size of all age classes remains constant over time, that is  $X(t) = X$  and  $Y(t) = Y$ .

The objective for MAY is to maximize the steady state level of harvest with respect to reserve size:

$$\text{MAX}_S \quad W(F^X X + F^Y Y) \cdot \left(\frac{E}{1-S}\right),$$

where  $F^X$  and  $F^Y$  are  $n \times n$  fishing mortality matrices with age specific mortality coefficients  $F^X(k)$  and  $F^Y(k)$  along the diagonal and zeros elsewhere. The steady-state harvest is the sum of the products of age specific mortality fishing mortality coefficients, number in each age class, fish weight by age class, and intensity of effort.

Reserve size is a percentage of total fishing area and ranges between 0 and 1:

$$0 \leq S < 1.$$

Since the objective is to maximize the value of fishing productivity,  $S$  should never equal 1. If  $S = 1$ , the entire area is closed to fishing, which obviously cannot maximize harvest (or at least the legal harvest).

We find the maximum harvest by finding the maximum of (5) with respect to reserve size subject to the population dynamics equations (1) - (4), and reserve size constraint (6).

If the reserve size constraint is binding, then  $S = 0$ . This implies that the net value of the reserve is negative. If the marginal gain from a reserve decreases with reserve size, then the marginal loss in value 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 reserve size constraint is nonbinding,  $S > 0$ . Here the net 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.

In contrast to maximizing annual yield, determination of the dynamic optimum requires summing discounted harvests over the entire time horizon:

$$\underset{S}{\text{MAX}} \quad \sum_{t=0}^{\infty} \left(\frac{1}{1+i}\right)^t P W(F^X X(t) + F^Y Y(t)) \cdot \left(\frac{E}{1-S}\right),$$

where  $i$  is the discount rate and  $P$  is fish price per unit. The dynamic optima is the NPV of cumulative harvests maximized with respect to reserve size.

The reserve size that maximizes the NPV of the path of harvest depends on the initial state of the fishery and reserve, which is assumed to be known. The initial age class structure is:

$$X(0) = X_0; \quad Y(0) = Y_0$$

We find the reserve size that maximizes the NPV of the path of harvests by determining the maximum of (9) with respect to reserve size subject to the population dynamics equations (1) - (4), the reserve size constraint (6) and initial conditions (8).

Although the objective is now to maximize net present value over time rather than maximizing biological production, interpretation of the reserve size constraint is similar to the steady state model. If the reserve size constraint is binding, then  $S = 0$ . This implies that the net value of the reserve is negative. The loss in value from closing the fishing area exceeds the gain in value from protecting some fish in a reserve for all reserve sizes. If the constraint is nonbinding,  $S > 0$ , and the net value of the reserve is positive for some range. The gain in value from protecting some fish in a reserve exceeds the loss in value from reducing the area open to fishing.

## Simulation Methodology

### Population Dynamics of the Simulation

A simulation model provides insight into the impacts of reserves on fishery population and harvest. The simulation illustrates the impact on fishery production and optimum reserve size of varying several key parameters including: effort levels, recruitment, emigration rates, and growth rates. Because of the uncertainties surrounding many of the biological parameters, we do not expect the simulation results to yield accurate quantitative data on the impacts of reserves. The purpose of the simulation is to illustrate the economic ramifications of a range of commonly-held biological assumptions. We model the simulation using STELLA™<sup>7</sup> a dynamic differential equation solver.

Following equations (1) and (2) of the model, the simulation separates fish by age class and their location inside or outside the reserve. We use data on age specific growth rates, natural and fishing mortality, and fertility of red snapper from the gulf of Mexico (Goodyear 1992) to examine a tropical reef fishery. Although the model considers only a single species, the simulation may be a reasonable approximation of a multi-species fishery. Snapper are an important target species in many reef fisheries and have biological, behavioral, and reproductive characteristics in common with most important target species from reef fisheries (Bohnsack 1990). These characteristics include: a pelagic larval stage, limited movement of adults, and an exponential relationship between weight and fertility. With a pelagic larval stage, eggs and larvae float in the water column for an extended period of time. They are spread geographically by ocean currents, wind, and tides.

The simulation procedure begins with a steady state population structure corresponding to a particular level of fishing effort and no reserve. We then impose a reserve, closing a fraction of the area of the fishery. We simulate population and fishery dynamics until we reach a new steady state. Following equations (3) and (4) of the model, the simulation, incorporates a stock recruitment relationship. The increase in spawning stock biomass of the reserve population reflects increased recruitment in both the reserve and fishery.

### **Finding the Optimal Reserve Size**

We use a repeat optimization to determine reserve sizes that maximize annual yield (MAY) and the NPV of cumulative harvest for several levels of effort. It reports both the steady-state harvest levels, and the net present value of cumulative harvests, objective functions (5) and (9), respectively, for a range of reserve sizes and effort levels.

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 .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-fished.

Since there is incomplete information and differing opinions regarding some biological assumptions, we performed additional simulations with varied assumptions about larval mixing, density dependent emigration, and density dependent growth. We also tested the model for sensitivity to emigration rates and their responsiveness to spatially varying biomass densities.

# Notes

1. Governments may ignore artisanal fisheries because they have little visible impact on the formal economy and because fishers in general tend to resist regulation.
2. For many important fish species, larger fish have many, many times the eggs of smaller specimens. For instance one 60 cm. red snapper will produce as many eggs as 212 females of 41 centimeters (Bohnsack 1990).
3. The assumption of single species limits the applicability of the model in multiple species fisheries. It is extremely difficult to work with multiple species models with interactions. 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).
4. Alcala and Russ (1990) postulate that emigration of fish from densely- to less-densely populated areas is likely to occur in response to shortage of sleeping sites though not from food resource limitations. Doherty and Williams (1988), however, conclude that "there is little evidence of resources saturation at natural densities." In the model and simulation, we assume emigration to be density-dependent. In an additional simulation run, we relaxed this assumption, resulting in significantly larger optimal reserve sizes.
5. Many people believe that resources do not limit reef fisheries even in the unfished state (Doherty and Williams 1988). There is little support for density-dependent mortality, however, there is some support for density-dependent growth rates, particularly at young ages. This may be less a function of resource availability than competition for territory.
6. 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 exists that only an explicitly spatial model could capture fully.
7. STELLA™ is an icon-based programming package developed by High Performance Systems for use on Macintosh computers.
8. We present values relative to the maximum sustainable yield (MSY) that occurs at the .75 level of effort (i.e. all values were multiplied by a fraction such that the "annual harvest" and "NPV harvest" values for the .75 effort level equal 1000).

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