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YOU CAN HAVE YOUR FISH AND EAT IT, TOO: THEORETICAL APPROACHES TO MARINE RESERVE DESIGN

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ABSTRACT

Increasing fishing activity on coral reefs threatens both their fisheries and biodiversity. Marine fishery reserves, areas in which fishing is permanently prohibited, offer potential economic and conservation benefits. Despite their strong potential, we lack a fundamental understanding of the design of marine fishery reserves. Computer models -- in which fish life history, movement dynamics, and fishing pressure are included -- predict that reserves can maintain productive fisheries even if they encompass large proportions of management areas. Moreover, the models suggest that reserves will increase the persistence of easily over-harvested species and will also decrease year-to-year variations in catches. The reserve design that will maximize long-term fish catches depends on the life history, larval dispersal, and adult movement dynamics of the target species, as well as the fishing effort in the management area. Nevertheless, these computer models predict that the use of marine fishery reserves is an effective general fishery management technique, useful in particular for multi-species fisheries, and which also provides significant conservation benefits.

INTRODUCTION

World-wide, marine fisheries are in distress. In recent years figures show that global fishery yields have dropped for the first time despite expanding fleets, more efficient equipment, and efforts directed at previously unexploited stocks (Food and Agriculture Organization 1995). Many fish stocks declined in areas where resources are lacking for adequate management. However, even intensively managed fisheries have crashed in recent years (Norse 1993).

Marine fishery reserves, areas permanently closed to fishing, have the potential to maintain productive fisheries even in areas where management resources are lacking. As a fishery management strategy, reserves offer simple enforcement, conservation benefits, and fishery enhancements (e.g., Roberts and Polunin 1991; Rowley 1994; Bohnsack 1996). Reserves are simpler to enforce than traditional management techniques because they do not require inspection of catches or gear. Moreover, once established, the reserves become a common resource for fishers and encourages them to police themselves. Reserves also provide conservation benefits by protecting fish populations from over-fishing (Sladek Nowlis and Roberts, in preparation) and ecosystems from damaging fishing practices (Roberts 1995). Finally, management areas with reserves can provide catches that meet or exceed the maximum catches if a reserve were not used, while also reducing uncertainty in annual fish catches caused by environmental fluctuations (Sladek Nowlis and Roberts, in preparation).

To attain the long-term benefits associated with marine fishery reserves, fishers and managers must accept short-term losses when reserves are established because fishers have less area to fish. Using existing models of marine fishery reserve function (Sladek Nowlis and Roberts, in preparation), we asked several questions about these short-term losses.

1) How does fishing intensity, assumed to remain constant before and after reserve establishment, affect the speed at which reserve benefits offset losses from reduced fishing grounds?

2) How does reserve size affect the speed at which reserve benefits offset losses from reduced fishing grounds?

3) Is fishing intensity or reserve size more important in determining the rate at which benefits are achieved?

4) Can losses from reduced fishing grounds be minimized by phasing in reserves over several years and does a phasing in approach result in higher or lower overall catches in the long run?

METHODS

To investigate these questions, we developed size-classified life history models, described by Sladek Nowlis and Roberts (in preparation). In the models, fish eggs develop into newly settled fish and these fish grow through several size classes. Fish face natural and fishing mortality (the latter only outside reserves) and can contribute to the future population through reproduction. We varied reserve size (proportion of the total management area in which fishing is prohibited) and fishing intensity (proportion of the naturally-surviving fishery-recruited fish that are caught each year) and examined their influence on long-term fishery yields.

The key assumptions of our models addressed movement of fish and eggs or larvae between reserve and fishing areas. We assumed that adults stay in the area where they settled while eggs and larvae disperse widely across reserve boundaries. The majority of coral reef fish and invertebrate species disperse narrowly as adults and widely as larvae (Boehlert 1996). Even in cases where adults move widely or eggs and larvae move short distances, the assumptions of the model can be met and valid conclusions drawn if the reserve area is broken into appropriately-sized units (Sladek Nowlis and Roberts, in preparation).

Using the best available life history data for two exploited species of Caribbean reef fish, the queen trigger fish *Balistes vetula* (Aiken 1975; Houde 1989) and the white grunt *Haemulon plumieri* (Darcy 1983; Houde 1989), we adapted these models to examine short-term losses in fisheries associated with reserve establishment. In all cases, we determined the stable size-distribution and density of fish under a fixed fishing intensity and no reserve. We then took this stable population, created a reserve within its geographic range, and tracked annual catches for up to 100 years, making particular note of the time it took until fishery yields exceeded their productivity prior to reserve establishment.

We determined the effect of fishing intensity by establishing 20% reserves in queen trigger and white grunt fisheries over a range of fishing intensities. We studied the effect of reserve size by establishing a variety of reserve proportions for each species at a fixed fishing intensity of 0.2. We then studied the interaction of reserve size and fishing intensity by comparing the responses of fisheries that varied in their fishing intensities and in their reserve proportion. To compare equivalent pairs of fishing intensity and reserve proportion, we chose the optimal reserve proportion -- the proportion that produced the highest long-term yields in our models -- at various fishing intensities. For both of these species, sustainable yields are similar across a wide array of fishing intensities if optimal reserve proportions are used (Sladek Nowlis and Roberts, in preparation).

Finally, we determined how a phasing in of reserves might affect both short-term and long-term fishery yields. To do so, we used a white grunt population experiencing a fishing intensity of 0.2. We established an optimally-sized reserve of 37% and compared the short-term, long-term, and cumulative fish catches when the reserve was phased in over 1, 5, and 10 years. We phased in reserves by adding equal portions to the reserve each year for the time specified. Consequently, we established the whole 37% reserve at once for the 1 year case while for the 10 year case, we closed 3.7% of the management area each year for 10 years.

RESULTS

Reserves were only effective at increasing fish yields when the fisheries were over-fished in the absence of a reserve (Sladek Nowlis and Roberts, in preparation). In the absence of a reserve, the queen trigger had its maximum sustainable yield at a fishing intensity (FI) of 0.094, while the white grunt had its maximum sustainable yield at a fishing intensity of 0.117. Both were over-fished at higher fishing intensities and we only examined these cases (i.e., those where reserves would lead to a long-term increase in catches).

Heavily over-fished fisheries recovered fastest from losses associated with reserve establishment (Fig. 1). Both queen trigger and white grunt populations rebounded above pre-reserve productivity faster the more heavily they were over-fished. We established a 20% reserve for the queen trigger, the optimal size for this species under a fishing intensity of 0.125. While the lightly over-fished population (FI = 0.125) took nearly 30 years to recover from lost fishing grounds, the heavily over-fished population (FI = 0.2) recovered in half the time. Similarly, the heavily over-fished white grunt population (FI = 0.225) recovered more quickly than less-heavily over-fished populations when a 17% reserve was established (the optimal size for the white grunt under 0.15 fishing intensity). Both species recovered more quickly from reserve establishment losses if they were in bad shape to begin with.

Results were less clear when we held fishing intensity constant and varied only reserve size. When we established reserves for a heavily over-fished queen trigger population (FI = 0.2), larger reserves led to faster recovery than small reserves (Fig. 2). In contrast, smaller reserves made up losses faster when we established them for a less-heavily over-fished white grunt population (FI = 0.2). In both cases, the larger reserves (optimal size in both cases) lead to higher catches than smaller reserves within 30 years. However, recovery time could increase or decrease with increasing reserve size, depending on the fish species and fishing intensity.

When we varied both fishing intensity and reserve size, we found that fishing intensity was generally more impor tant in determining the speed to recovery from fishery reserve establishment losses. To compare equivalent pairs of fishing intensity and reserve proportion, we chose the optimal reserve proportion for any given fishing intensity. We found, as we did when just varying fishing intensity, that reserves led to more rapid population recovery when the populations were heavily over-fished prior to reserve establishment (Fig. 3). As was true when just fishing intensity was varied, heavily over-fished queen trigger populations (FI = 0.2) reached pre-reserve productivity levels in half the time of lightly over-fished populations (FI = 0.125). White grunts showed an even more dramatic pattern, with the most heavily over-fished populations recovering in one-third the time of the least over-fished. Despite their quicker recovery to pre-reserve productivity, note that the heavily over-fished populations are still the least productive after 30 years.

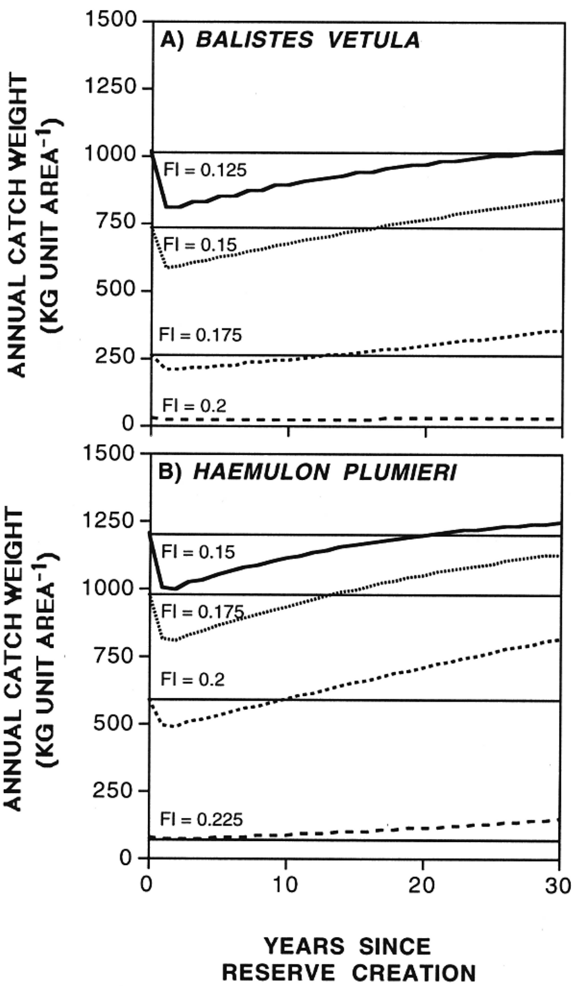

Fig. 1: Fishing intensity and fishery recovery following reserve establishment. (A) *Balistes vetula*, the queen trigger fish, with 20% of the management area closed to fishing. (B) *Haemulon plumieri*, the white grunt, with 17% of the management area closed to fishing. Each line represents the annual fish catches (in kg unit area^{-1}) following reserve creation. Catches in year 0 were the stable catches at the specified fishing intensity (FI) with no reserve. Fisheries recovered to pre-reserve productivity (indicated by thin solid lines) faster the heavier the fishing intensity.

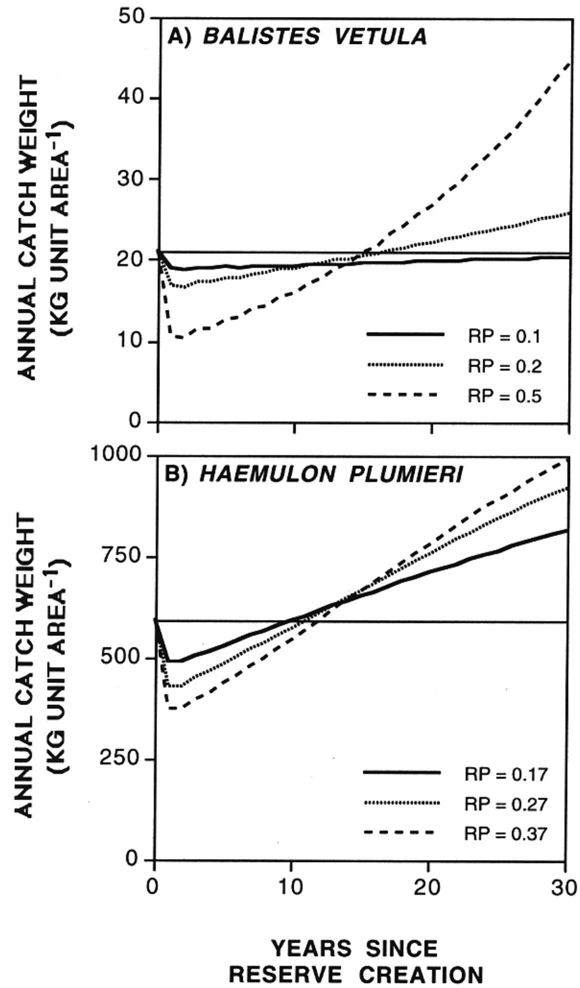

Fig. 2: Reserve size and fishery recovery following reserve establishment. (A) *Balistes vetula*, the queen trigger fish, with a fishing intensity of 0.2. (B) *Haemulon plumieri*, the white grunt, with a fishing intensity of 0.2. Reserves varied in size (RP = reserve proportion) from small reserves to the optimal reserve proportion for each species at this fishing intensity. Speed of recovery to pre-reserve productivity (indicated by the thin solid lines) did not vary consistently with reserve size. Smaller reserves caused smaller initial losses in fishery productivity but also reaped fewer rewards in the long run.

When we phased in reserves over periods of up to 10 years, we found that we could reduce short-term reserve losses but at the expense of long-term reserve gains (Fig. 4a). We established an optimally-sized 37% reserve for a white grunt population experiencing a fishing intensity of 0.2. The longer we took to phase in the re serve, the shallower the initial dip in annual fish catches. Therefore, fishers and managers would have relatively better early years if reserves are phased in over a long period of time. However, phased in reserves took longer for catches to exceed pre-reserve levels and had lower annual catches for over 50 years. We used cumulative catches -- the sum of all catches since reserve establishment -- to examine whether short-term gains or long-term losses from a phasing in approach were greater. To aid in comparison, we subtracted the cumulative catches from a reserve created in a single year from all cumulative catches (Fig. 4b). These results show that while the total catch over the first 10 to 15 years is higher when reserves are phased in, the total catch over the first 20 or more years is higher when reserves are created in a single year (Fig. 4b). In the long run, total catches since reserve creation from management areas where reserves are created in a single year exceed total catches since reserve creation from management areas where reserves are phased in.

DISCUSSION

Reserves do cause short-term fishery losses because they remove fishing grounds. However, these losses may be minor in many cases and can be addressed through other management measures. In all of our runs, short-term losses were worst within the first year or two, and catches dropped from previous years by a proportion similar to the reserve proportion. When 50% of an area was set aside as a reserve, this could mean a 50% reduction of catch in year 1 (Fig. 2a). However, very large reserves were only appropriate for increasing yields of extremely heavily over-fished populations (Sladek Nowlis and Roberts, in preparation). In these cases, fishers have so much to gain from reserve establishment and it may be more tractable to make up their relatively small (in magnitude, not proportion) short-term losses through other programs, including subsidies or alternate business opportunities. We found that these heavily over-fished fisheries also recovered most quickly, in as little as 7 years (Fig. 2b). Note that at 'recovery' these previously heavily over-fished fisheries still have years before they reach their peak potential productivity. Less heavily over-fished fisheries took longer to recover but also experienced smaller losses and higher overall yields.

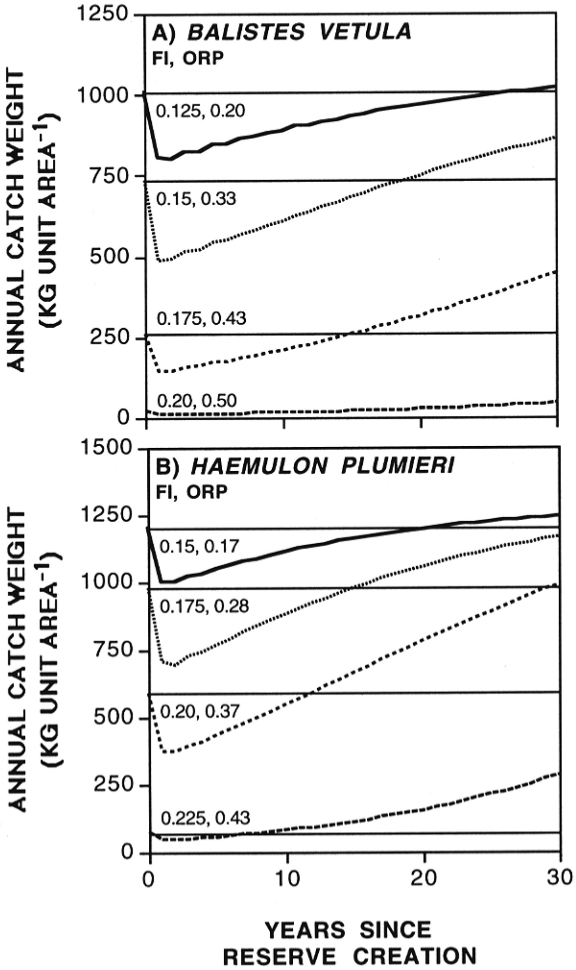

Fig. 3: Combined effects of fishing intensity and reserve size on fishery recovery following reserve establishment. A) *Balistes vetula*, the queen trigger fish. (B) *Haemulon plumieri*, the white grunt. For equivalency, we used optimal reserve proportions for each fishing intensity. As with patterns based on fishing intensity, fisheries recovered faster the more heavily fished they were prior to reserve establishment. Reserve sizes primarily affected the magnitude of initial fishery losses but did not significantly influence the speed of recovery (compare to Fig. 1).

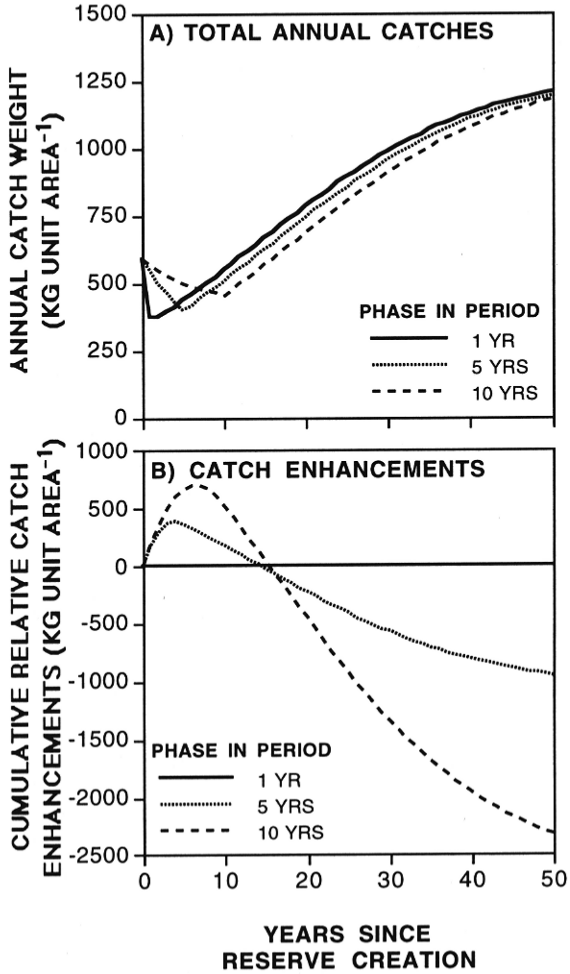

Fig. 4: Phasing in reserves, fishery recovery, and long-term effects. (A) Total annual catches. (B) Cumulative relative catches, calculated by adding all the fish catches since reserve creation and subtracting the cumulative catches for the same period of a reserve created all at once. Reserves phased in over a series of years had better initial catches because more fishing grounds were available in early years. However, the phasing in of reserves delayed reserve benefits, condemning phased in reserves to lag behind a reserve created all at once for 50 more years. In the long run, cumulative catches are lower for reserves phased in over several years, as the reduced initial losses from phasing in are outweighed by the delay in reserve benefits.

We were encouraged that reserve size had less of an effect on recovery time than fishing intensity. It is not surprising because reserve size influences both the amount of short-term loss and the amount of long-term benefit. For example, we might expect a small reserve to recover more quickly because it will create smaller short-term losses in fishing grounds. However, we might also expect it to recover more slowly because a small reserve will provide fewer long-term benefits. These short- and long-term forces balance out in a way that is not particularly dependent on reserve size. This result implies that managers can design reserves to effectively enhance fisheries in the long run without strongly influencing how long it takes for the fishery to recover to pre-reserve productivity. The time to recovery is affected more by the state of the fishery prior to reserve establishment. If it was in fairly good shape, the recovery will be slow but the losses mild (in proportion, not magnitude). If it was in poor shape, the recovery will be more rapid but the initial losses more extreme.

If reserve establishment will cause unacceptable hardships, they can be phased in to reduce short-term losses (Fig. 4a). The worst year when a reserve was phased in over 10 years resulted in approximately half the productivity loss of the same reserve created all at once. The disadvantage of the phasing in approach is that it slows the speed at which reserve benefits accumulate. For example, the reserve that was phased in over 10 years took several years longer before productivity had returned to pre-reserve levels. Moreover, the phased in reserve continued to under-perform the reserve established all at once for over 50 years. Consequently, the cumulative catches -- the total weight of fish caught since the reserve was created -- was lower when reserves were phased in. The phasing in approach can be useful if managers need to minimize initial losses in productivity, but it actually reduces the speed of recovery and long-term catches.

Marine fishery reserves have many important benefits, including ease of enforcement, increased long-term fish yields, and enhanced conservation of marine species and ecosystems (Bohnsack 1996). However, we cannot forget that reserve establishment will cause short-term losses to fishers. Fortunately, these losses can be mild or quickly recovered, depending on the status of the fishery prior to reserve establishment. If these short-term losses are likely to over-burden fishers, managers can opt for a phasing in approach, or they could compensate fishers for losses in the early years following reserve establishment. Phasing in offers higher short-term catches, but larger losses in time to recovery and future productivity.

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REFERENCES

Aiken KA (1975) The biology, ecology and bionomics of the triggerfishes, Balistidae. In: Munro JL (ed) Caribbean coral reef fishery resources. Institute for Caribbean and Latin American Regional Management pp 191-276.

Boehlert GW (1996) Larval dispersal and survival in tropical reef fishes. In: Polunin NVC and Roberts CM (eds) Reef fisheries. Chapman and Hall, London pp 61-84.

Bohnsack JE (1996) Maintenance and recovery of fishery productivity. In: Polunin NVC and Roberts CM (eds) Reef fisheries. Chapman and Hall, London pp 283-313.

Darcy GH (1983) Synopsis of biological data on the grunts *Haemulon aurolineatum* and *H. plumieri* (Pisces: Haemulidae). National Oceanic and Atmospheric Administration Technical Report NMFS Circular 448.

Food and Agriculture Organization (1995) The state of the world fisheries and aquaculture. Food and Agriculture Organization of the United Nations, Rome.

Houde ED (1989) Comparative growth, mortality and energetics of marine fish larvae: temperature and implied latitudinal effects. Fish Bull, US 87:471-495.

Norse EA (1993) Global marine biological diversity. Island Press, Washington, DC.

Roberts CM (1995) Effects of fishing on the ecosystem structure of coral reefs. Cons Biol 9:988-995.

Roberts CM and Polunin NVC (1991) Are marine reserves effective in management of reef fisheries? Rev Fish Biol Fish 1:65-91.

Rowley RJ (1994) Marine reserves in fisheries management. Aquat Conserv 4:233-254.