Marine Reserves:
What Would They Accomplish?

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Abstract   *A marine reserve is defined as a subset of the area over which a fish stock is dispersed and closed to fishing. This paper investigates what will happen to fishing outside the marine reserve and to the stock size in the entire area as a result of establishing a marine reserve. Three regimes are compared: (i) open access to the entire area, (ii) open access to the area outside the marine reserve, and (iii) optimum fishing in the entire area. Two models are used: (i) a continuous-time model, and (ii) a discrete-time model, both using the logistic growth equation. Both models are deterministic equilibrium models. The conservation effect of a marine reserve is shown to be critically dependent on the size of the marine reserve and the migration rate of fish. A marine reserve will increase fishing costs and overcapitalization in the fishing industry, to the extent that it has any conservation effect on the stock, and in a seasonal fishery it will shorten the fishing season. For stocks with moderate to high migration rates, a marine reserve of a moderate size will have only a small conservation effect, compared with open access to the entire area inhabited by a stock. The higher the migration rate of fish, the larger the marine reserve must be in order to achieve a given level of stock conservation. A marine reserve of an appropriate size would achieve the same conservation effect as optimum fishing, but with a smaller catch.*

Key words   Bioeconomic analysis, fisheries economics, fisheries management, marine reserve.

Introduction

Recently, the idea that certain areas be closed to fishing has gained popularity. This idea has developed in the wake of persistent overfishing and occasional stock collapses, the most recent of which is the northern cod disaster on the Grand Banks. The northern cod disaster is particularly disturbing since it took place despite a high degree of control over the harvest by the Canadian government, which was committed to a moderate rate of exploitation and whose marine science and scientists must be ranked as world class. Seen against this background, it would clearly be desirable to use fisheries management strategies that would work independently of incomplete information on stocks and catches and less-than-fully-effective enforcement policies.

How effective would the protected areas, or marine reserves as they are often called, be in protecting fish populations? Would this not depend on the size of the area protected and the rate at which fish disperse? It would appear that a marine reserve need not be very effective if the mobility of fish in and out of the protected area is high. How would the industry respond? If the conservation policy is successful, would not excessive fishing capacity be built up in response to improved conditions in the area still open to fishing, defeating, at least, the economic gains of this policy and possibly even the conservationist advances as well?

In this paper, we investigate the economic and conservationist effects of marine reserves and how they depend on the migration rate of fish, the cost of fishing, and the size of the marine reserve. We use the logistic growth model and start with the continuous-time formulation, as this is the most simple and elegant approach. Some features of seasonal fisheries are, however, necessarily ignored in this formulation, and, so, we also investigate a discrete-time model. To isolate the effects of marine reserves, it is assumed that a marine reserve is the only form of management imposed and that there is open access to the area outside the reserve.

The approach taken in this paper is deterministic. This is quite sufficient to capture the response of fishing effort and capacity to the establishment of marine reserves, and how the effectiveness of marine reserves depends on the migration rate of the fish. Previous investigations of this, such as Polacheck (1990), DeMartini (1992), and Holland and Brazee (1996) have concentrated on biological aspects, such as yield per recruit and changes in spawning stock biomass, using age-structured models of real-world fish populations, but taking fishing effort as given. The main focus in this study is on the reactions of the industry to the effects of marine reserves under an open-access regime. For this purpose, general biomass models seem adequate, despite their limited empirical applicability.

A Continuous Time Model

Consider a fish stock located in an area of unit size. Suppose the stock obeys the logistic law of growth, so that, in the absence of exploitation,

$$\frac{dS}{dt} = rS(1 - S) \tag{1}$$

where S is the size of the stock, and r is the intrinsic rate of growth. The stock is measured as a fraction of the carrying capacity of the area, which, thus, implicitly is set equal to unity.

Now let a fraction, m, of the area be set aside as a marine reserve. Let the stock in the two sub-areas be measured as densities, so that the carrying capacity of each subarea is also equal to unity. With the fish moving between the two sub-areas, equation (1) must be modified to take account of this. The size of the stock in the marine reserve is mS_m, where S_m is the density of the stock, and m is the size of the marine reserve. With fish moving at the rate z, the migration rate of the stock in the marine reserve will be zmS_m. The probability that a fish will migrate out of the reserve is $1 - m$, so the migration rate out of the reserve will be $(1 - m)zmS_m$. To translate this into change in stock density in the area outside the reserve, we divide by the size of that area, $1 - m$, so that the increase in the density of fish in the area outside the marine reserve due to migration from the marine reserve will be zmS_m. Similarly, $mz(1 - m)S_o$ is the rate of migration into the marine reserve, and the change in the density of fish outside

the marine reserve due to this out-migration will be $-zmS_o$, where o denotes the "other" sub-area, *i.e.*, the area outside the marine reserve.[1] Thus, the rate of change in the density of fish outside the marine reserve is

$$\frac{dS_o}{dt} = rS_o(1 - S_o) + zm(S_m - S_o) - Y \qquad (2a)$$

where Y is the catch rate of fish outside the marine reserve, expressed as density. By a similar reasoning, the rate of change in the density of fish in the marine reserve is

$$\frac{dS_m}{dt} = rS_m(1 - S_m) + z(1 - m)(S_o - S_m). \qquad (2b)$$

In equilibrium, the density of the stock in the marine reserve will be

$$S_m = -\frac{1}{2}\left[\frac{(1 - m)z}{r} - 1\right] + \sqrt{\frac{1}{4}\left[\frac{(1 - m)z}{r} - 1\right]^2 + \frac{(1 - m)zS_o}{r}} \qquad (3)$$

with open access prevailing outside the marine reserve, $S_o = c$, where c is the stock density at which the fishery breaks even.[2] Substituting c for S_o in equation (3) we can find S_m, and from equation (2a), the equilibrium catch rate, the catch in weight units being $(1 - m)Y$.

  In the following, we shall compare a policy of marine reserve with open access outside the reserve to two alternative regimes, open access to the entire area, and optimum fishing in the entire area. Under open access, the equilibrium stock density will be c, as previously stated. We define optimum fishing as that which maximizes sustainable rent per year, thus ignoring discounting of the future

$$\max rS(1 - S)\left(p - \frac{c}{S}\right) \qquad (4)$$

where p is the price of fish, and c is a cost parameter. This formulation implies that the unit cost of fish is inversely proportional to the exploited stock, or that the catch per unit of effort is proportional to the stock, with a constant unit cost of effort. With $p = 1$, the optimum stock[3] will be

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[1] This migration function is similar to the one used by Conrad (1997). He considers two areas with different carrying capacities, K_1 and K_2, and uses the migration function $s(S_1/K_1 - S_2/K_2)$. Here the carrying capacity is unity everywhere, and the diffusion rate, s, is the product of z and $m(1 - m)$.

[2] With the catch equation $Y = EqS$, E denoting effort and q being normalized at unity, profits in equilibrium will be $pES - cE$, so with zero profits, and p also normalized at unity the zero-profit stock will be $S = c$.

[3] Discounting the future at the rate δ would affect the optimum stock size. The formula for the optimum stock size with discounting is, in this case,

$$S = \frac{1}{4}\left[c + 1 - \frac{\delta}{r} + \sqrt{\left(c + 1 - \frac{\delta}{r}\right)^2 + \frac{8c\delta}{r}}\right].$$

Hence, for a given cost of effort, a positive discount rate would lower the optimum stock level. On the other hand, a positive discount rate raises the cost of fishing effort, c; the more it is raised, the more capital intensive the fishing technology is (Hannesson 1987). This increases the optimum stock level, so the impact of the discount rate on the optimum stock level is, in fact, ambiguous.

$$S = \frac{1 + c}{2}.$$ (5)

Figures 1 through 3 compare the three regimes, (*i*) open access to the entire area, (*ii*) open access to the area outside the marine reserve, and (*iii*) optimum exploitation in the entire area. Figure 1 shows the impact of fishing costs for a given size of the marine reserve (40% of the whole area) and a given migration rate ($z = 0.5$). The size of the stock in the entire area $[mS_m + (1 - m)S_o]$ is remarkably similar under both open-access regimes, with and without the marine reserve. As fishing costs approach zero, the population becomes extinct under both open-access regimes. This is a more serious case than the no-cost assumption might suggest, as this also covers the case where the unit cost of fish is insensitive to the size of the exploited stock (Hannesson 1993).

The catch level is also remarkably similar under both open-access regimes; if fishing costs are low, the stock is overexploited to the point that catch diminishes as the cost falls, as would, for example, happen as a result of technological progress. The maximum catch with a marine reserve is only slightly lower than when the entire area can be fished, and occurs at a slightly lower cost level. The equilibrium exploitation rate under both open-access regimes is also similar. The exploitation rate is an expression of the total effort applied, or the total cost of fishing. The total cost of fishing is about twice as high under both open-access regimes as with an optimal exploitation, without necessarily resulting in greater catch.

Figure 2 shows the effect of varying the size of the marine reserve for a given and relatively low cost of fishing (under open access, the stock would be reduced to 15% of its pristine level). With a relatively large reserve (80% of the entire area), the equilibrium stock would be the same as the optimum one, even if there was open access outside the reserve.[4] The maximum catch with a marine reserve and open access outside is not quite as great as the optimum one, but the stock is smaller and the exploitation rate (total costs) higher (the maximum catch is obtained when the marine reserve is about 75% of the total area).

Finally, figure 3 shows the effect of varying the migration rate. Not surprisingly, as the migration rate increases, the marine reserve solution approaches the solution with open access to the entire area. With the fish redistributing themselves rapidly, it makes no difference whether a part of the area is closed, or open, to exploitation. If the fish do not move around at all ($z = 0$), the total stock is almost as large as with optimal exploitation, but the catch is much lower. The exploitation rate is also lower, but since the regime is open access, there are no rents, and the revenue is fully absorbed by fishing costs.

A Discrete Time Model

Considering the problem in discrete time brings out distinctions which one may expect to encounter in fisheries with a seasonal character. The discrete-time analogue of the above model is the following

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[4] From the top panel of figure 2, we see that the effect of the size of the marine reserve on the equilibrium stock is not very great until the size of the reserve is quite substantial (about one-half of the area). Hence, even if a positive discount rate would reduce the optimum standing stock, the effect on the size of the reserve needed to achieve this would not be very great. For example, with $c = 0.15$, a discount rate of 5%, and ignoring the effect of the discount rate on c, the optimum stock would be 0.48, compared to 0.57 in the absence of discounting, using the formula in footnote 3. The marine reserve would still need to be almost 80% of the entire area to achieve this stock level.
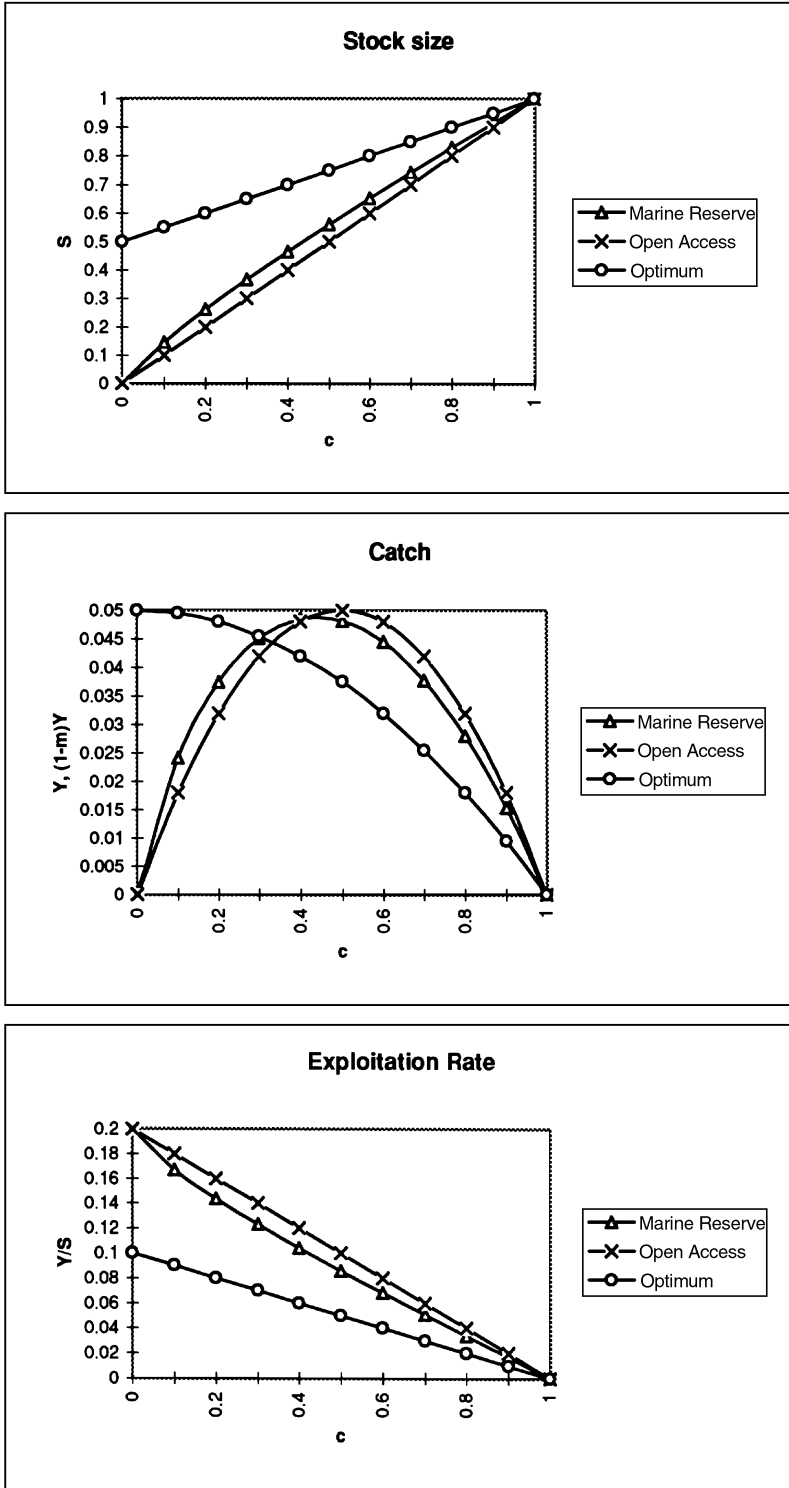
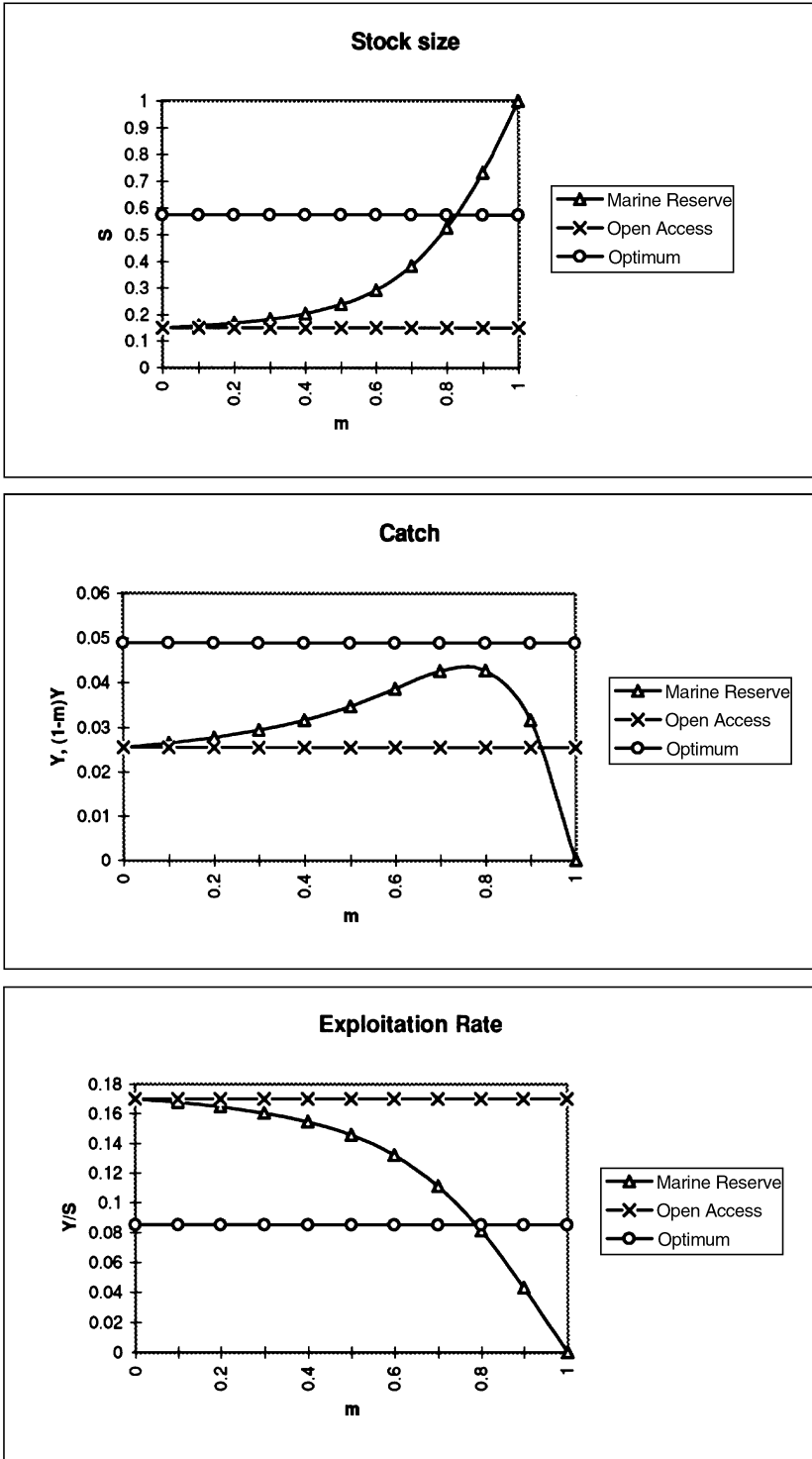**Figure 1.** Effect of Varying Cost ($m = 0.4$; $z = 0.5$; $r = 0.2$)

Stock size

Catch

Exploitation Rate

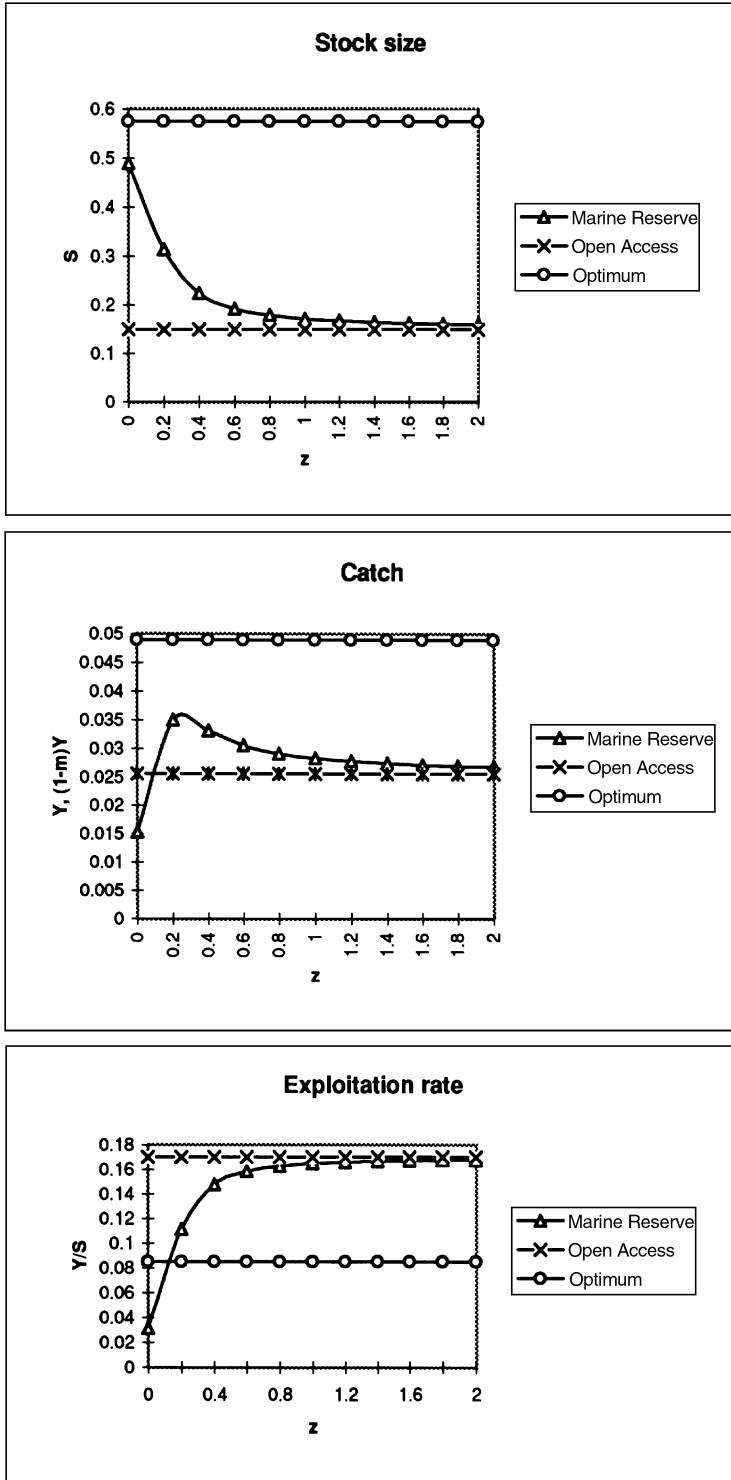**Figure 2.** Effect of Varying Size of Reserve ($c = 0.15$; $z = 0.5$; $r = 0.2$)

Figure 3. Effect of Varying Rate of Migration ($c = 0.15$; $m = 0.4$; $r = 0.2$)

$$R_{o,t} = S_{o,t-1} + rS_{o,t-1}(1 - S_{o,t-1}) + zm(S_{m,t-1} - S_{o,t-1}) \tag{6a}$$

$$R_{m,t} = S_{m,t-1} + rS_{m,t-1}(1 - S_{m,t-1}) + z(1 - m)(S_{o,t-1} - S_{m,t-1}). \tag{6b}$$

This formulation implies that fishing is concentrated at the beginning of each period, during which the stock is fished down from R_t, the level at the beginning of period t, to S_t. During the harvesting phase, the fish do not move into or out of the marine reserve, but the stock that remains outside the marine reserve after fishing intermingles with the stock inside the marine reserve. This aggregate stock determines the net growth of the stock, and the resulting stock disperses itself randomly over the entire area. These two processes determine the stock available at the beginning of the next period.

In equilibrium, $R_m = S_m$, and the solution for S_m is the same as in equation (3). With the unit operating cost of fish inversely proportional to S and equal to c/S, the stock density outside the marine reserve will be depleted to $S_o = c$. Again, we compare this regime to open access to the entire area (in which case the stock density at the end of the fishing season will be c) and optimum fishing in the entire area. Maximizing sustainable rent in this model, including the contribution to capital costs (fixed costs), entails

$$\max R(S) - S - c[\ln R(S) - \ln S] \tag{7}$$

as the total operating cost is

$$\int_S^R \frac{c}{x} \, dx = c(\ln R - \ln S).$$

The first order condition is

$$R'(S) - 1 - c\left[\frac{R'(S)}{R(S)} - \frac{1}{S}\right] = 0. \tag{8}$$

From this we can find the optimum density as

$$S = \frac{1}{2}\left(\frac{2 + 3r}{2r}\right) - \sqrt{\frac{1}{4}\left(\frac{2 + 3r}{2r}\right)^2 - \frac{1 + r + c}{2r}}. \tag{9}$$

The results, with respect to equilibrium stock and yield, are similar to the continuous model. What is new here is that intra-seasonal rents emerge; instead of keeping the stock always at the equilibrium level, continuously creaming off the surplus growth, we start with a bigger stock at the beginning of each season and deplete it until the operating cost per unit of fish has risen to the level where it is equal to the price. The top panel of figure 4 shows the intra-seasonal rents with open access to the area outside the marine reserve, open access to the entire area, and optimal fishing. Under open access, the intra-seasonal rents are higher with the marine reserve. Due to migration from a more plentiful stock in the reserved area, we always start with a higher density outside the marine reserve than we would with open access to the entire area.

The intra-seasonal rents are quasi-rents; *i.e.*, revenues exceeding operating
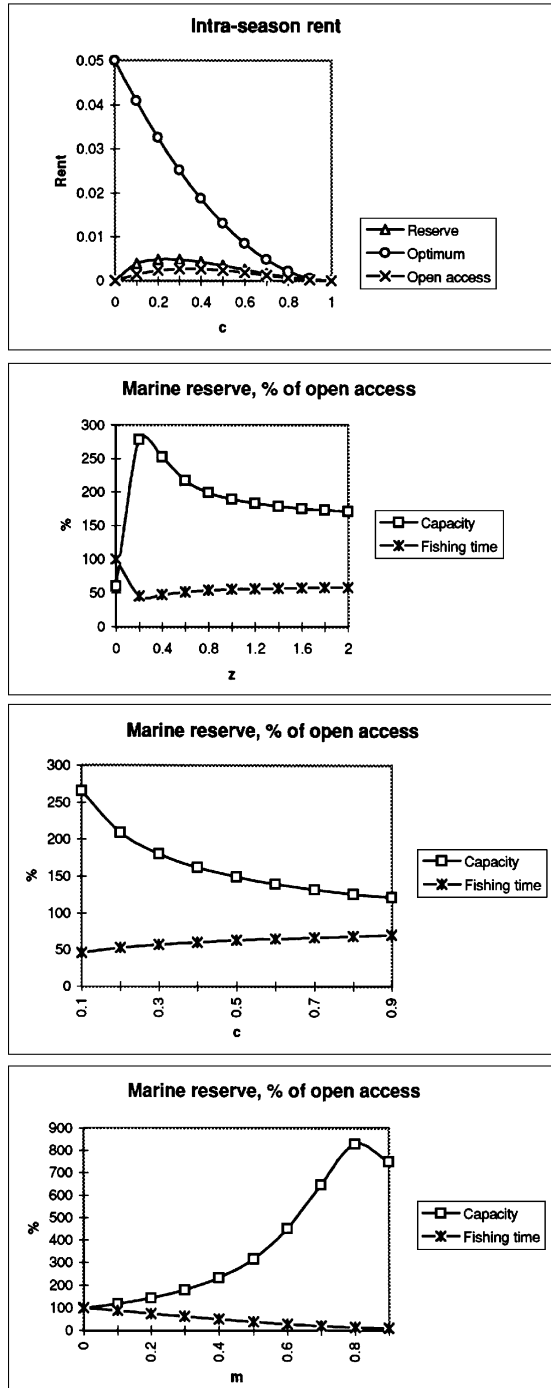
Figure 4. Effect of Marine Reserve on Intraseason Rent,
Fishing Capacity, and Season Length

Note: The second, third, and forth panel diagrams show the results of varying c, z, and m.
The values of these when held fixed are $c = 0.15$, $m = 0.4$; and $z = 0.5$, while $r = 0.2$.

costs. It is to be expected that these rents will attract investment in fixed capital, the cost of which is independent of the rate of utilization in the fishing season. Assuming that investments in fishing capacity are proportional to these quasi-rents, we get the results shown in figure 4, where we compare the fishing capacity with open access outside the marine reserve to open access to the entire area. The excess capacity generated by the marine reserve is sensitive to the cost of fishing, migration rate of the fish, and the size of the marine reserve. For a marine reserve of 40% of the entire area, the fishing capacity is twice that under open access to the entire area when the cost of fishing is low. For a relatively low cost ($c = 0.15$), the fishing capacity with a marine reserve reaches a maximum of about eight times what it would be with open access to the entire area when the marine reserve is about 80%. For a marine reserve of 40% and a cost of $c = 0.15$, the fishing capacity is two to three times the open-access level, except for very low migration rates. In these scenarios, one of the main results of establishing the marine reserve is to encourage overinvestment in fishing capacity.

An associated effect is a shortening of the fishing season, as it will take less time to deplete the population to the break-even level the larger the fishing capacity is. The time it will take to deplete the stock to the level c is given by $Re^{-FT} = c$, where F is the fishing mortality produced by the fishing fleet, and the length of the fishing season (T) is $T = \ln(R/c)/F$. By assumption, the capacity of the fishing fleet is proportional to the intra-season rent. Now the fishing mortality produced by a unit of fishing capacity is inversely related to the size of the area in which the stock is confined, so if one unit of capacity produces fishing mortality, F^*, over the entire area, the mortality produced in the area outside the marine reserve will be $F^*/(1 - m)$. Hence, the relative length of the fishing season under open access with and without the marine reserve will be

$$\frac{T_{MR}}{T_{OA}} = \left[\frac{\ln R_{MR}}{\ln R_{OA}}\right]\left(\frac{V_{OA}}{V_{MR}}\right)(1 - m) \tag{10}$$

where V is rent, the subscript MR refers to the regime with open access to the area outside the marine reserve, and OA to open access to the entire area. Figure 4 shows the ratio T_{MR}/T_{OA} as a percentage. The higher capacity buildup generated by the higher intra-season rents with the marine reserve, results in a very substantial shortening of the fishing season. For example, when varying m in figure 4, the fishing capacity under open access with a marine reserve rises to a peak of more than eight times the level when the entire area is open, while the fishing season shrinks by more than 80%.[5]

Conclusion

The foregoing analysis suggests that little would be gained by establishing marine reserves without applying some measures that constrain fishing capacity and effort. The migration of fish ensures that the fish stock to be protected would be depleted despite the existence of a marine reserve. The catch might be larger than under open access to the entire area, but this gain would be nullified by increasing cost. The re-

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[5] The seasonal model in this section is in many ways similar to the approach taken by Homans and Wilen (1997). In their model, intraseason rents attract fishing capacity which regulators counteract by shortening the fishing season, as needed, to take a given total allowable catch.

sults also suggest that marine reserves would have to be very large, maybe 70% to 80% of the entire fishing area, in order to achieve yield and conservation effects on par with an optimally controlled fishery. However, the difference would be the erosion of economic benefits in the absence of any controls that reign in fishing capacity and effort. In a seasonal fishery, the increase in intra-season rents would lead to a buildup of greater fishing capacity, which, in turn, would lead to a shorter fishing season. These effects could be very substantial. As the existing literature indicates, marine reserves might provide a hedge against stock collapses (Lauck 1996; Lauck *et al*., 1998), but only if they supplement other management measures that keep effort and capacity in check. Marine reserves by themselves, without any measures to restrain fishing effort and capacity, might achieve little other than increasing the costs of fishing.

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Appendix

Stability of Equilibrium With Open Access Outside Marine Reserve

Continuous Model

Consider a perturbation of the linearized system [equations (2a) and (2b)] around the equilibrium point

$$\frac{dS_o}{dt} = \left[r(1 - 2S_o) - zm - \frac{\partial Y}{\partial S_o} \right] \Delta S_o + zm\Delta S_m = a_{11}\Delta S_o + a_{22}\Delta S_m$$

$$\frac{dS_m}{dt} = z(1 - m)\Delta S_o + \left[r(1 - 2S_m) - z(1 - m) \right] \Delta S_m = a_{21}\Delta S_o + a_{22}\Delta S_m.$$

We consider only the biological part of the system and hold the fishing effort constant. It may be noted, however, that the human part of the system could destabilize an otherwise stable biological system if the reaction to positive or negative profits is strong enough. With the catch function implicit in the previous analysis (cf. footnote 2), we have $Y = ES_o$, and so $\partial Y/\partial S_o = E$. Now, in equilibrium, $S_o = c$, and so $E = Y/c$, and $\partial Y/\partial S_o = Y/c$.

The characteristic equation is $\lambda^2 - (a_{11} + a_{22})\lambda + (a_{11}a_{22} - a_{21}a_{12}) = 0$ with roots

$$\lambda = \frac{1}{2}\left(\alpha \pm \sqrt{\alpha^2 - 4\beta} \right)$$

where $\alpha = a_{11} + a_{22}$ and $\beta = a_{11}a_{22} - a_{21}a_{12}$. For stability, we need at least one negative root, or a negative real part. In all cases reported, there is at least one negative root, but for some low values of m or c, there is one positive root, implying that the equilibrium is a saddle point. See Clark (1976, ch. 6), or Conrad and Clark (1987, pp. 45–48).

Discrete Model

A perturbation of the linearized system around equilibrium gives

$$\Delta S_{o,t+1} = \left[1 + r(1 - 2S_o) - zm - \frac{\partial Y}{\partial S_o} \right] \Delta S_{o,t} + \left(zm - \frac{\partial Y}{\partial S_m} \right) \Delta S_{m,t} = a_{11}\Delta S_{o,t} + a_{12}\Delta S_{m,t}$$

$$\Delta S_{m,t+1} = z(1 - m)\Delta S_{o,t} + \left[1 + r(1 - 2S_m) - z(1 - m) \right] \Delta S_{m,t} = a_{21}\Delta S_{o,t} + a_{22}\Delta S_{m,t}$$

As for the continuous model, we consider stability of the biological system, holding effort constant. The catch is given by $Y = R_o(1 - e^{-E})$. In equilibrium, $S_o = c = R_o e^{-E}$. Hence, $E = -\ln(c/R_o)$, and $\partial Y/\partial S_o = (\partial R_o/\partial S_o)(1 - c/R_o)$, and analogously for $\partial Y/\partial S_m$.

Stability of the equilibrium, S_o, S_m, requires, in this case, that the roots of the characteristic equation be less than 1 in absolute value, or have real parts that are less than 1 in absolute value. In the cases discussed in this paper, all roots are less than 1 in absolute value.