Marine protected areas in 'nonlinear' ecosystems

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Recd 19.03.03; Acceptd 30.06.03; Online 06.08.03

The very large changes observed within marine communities, owing to excessive harvesting, have been attributed to switches between alternative stable states. Correspondingly large reductions in overall fishing effort are usually difficult to implement. For such 'nonlinear' ecosystems, introducing large marine protected areas, with low to zero harvesting, but without reduction in overall fishing effort, can give a marked increase in total yield of the depleted stocks. These increases, however, are still less than can be achieved by reducing fishing effort.

Keywords: marine reserves; alternative stable states; overfishing; resource management

1. INTRODUCTION

Problems of gross over-fishing have led to concern, not only with decreased yields of fish, but also with severe impacts on the overall ecosystem (NRC 2001). There is great difficulty, socially or economically, in significantly reducing fishing effort or capacity. One alternative for moderating these impacts is to ban, or greatly restrict, fishing in some fraction of the fishing grounds (generically termed marine protected areas (MPAs)). The proposed fraction can be large; 25–40% in a recent study of the North Sea (Beattie *et al.* 2002). However, if the total fishing effort is not changed, there is a proportionate increase in the remaining area and the possible benefits may be dubious, especially for the fishery.

In any analysis the representation of the interactions between fish population growth, natural predation and mortality due to fishing is crucial. Recently (Scheffer *et al.* 2001), the severe and unexpected collapses and lack of recovery, for many fish stocks, have suggested that the simpler, single-species models need to be modified to include alternative stable states (ASS) that can cause fish stocks to switch relatively rapidly from 'domains' with high abundance to ones with low abundance, and to be less likely to switch back if fishing effort is reduced (Spencer & Collie 1997a,b). Figure 1 illustrates the magnitude of the change between two possible regimes, the ASS model fit and the apparent lack of a response.

We explore the relationships between ASS models and MPAs. The essential idea is that, if overall fishing effort is so great that the system is in the 'low' domain, then by decreasing effort sufficiently in part of the fishery to switch it to the 'high' domain, and allowing the corresponding increases in the remainder to leave the total effort unchanged, the overall yield will be significantly greater.

2. FISHERY MODELS

The canonical equation to give ASS is (Ludwig *et al.* 1978; May 1977)

$$\frac{dP}{dt} = aP \left(1 - \frac{P}{b} \right) - \frac{cP^2}{P^2 + d^2}, \quad (2.1)$$

where P is population density, a is growth rate, b is carrying capacity, c is predation rate and d is half-saturation level for predation, all in arbitrary units. The logistic term represents growth and the s-shaped response gives predation. This second term implies that the undefined predator is switching between P and a less-preferred food supply (Holling 1965). In fisheries models, the logistic term is combined with linear mortalities (Rothschild 1986) as

$$\frac{dP}{dt} = aP \left(1 - \frac{P}{b} \right) - fP - mP, \quad (2.2)$$

where f is the fishing effort and m represents the natural mortality. We combine equations (2.1) and (2.2) by replacing linear mortality with nonlinear predator switching. We take $a = d = 1$. The value $a = 1$ approximates the annual growth rate used for fish stocks (Steele & Henderson 1984; Spencer & Collie 1997a) so the time-scale for the following calculations is of the order of years. The resulting equation

$$\frac{dP}{dt} = P \left(1 - \frac{P}{b} \right) - \frac{cP^2}{1 + P^2} - fP \quad (2.3)$$

has been used to evaluate the effects of ASS in fisheries (Steele & Henderson 1984; Spencer & Collie 1996, 1997b; Collie & DeLong 1999). It will be applied here to explore the consequences of ASS in relation to the use of MPAs. We take $b = 10$ and $c = 1$ (Spencer & Collie 1996). For bifurcation, it is necessary that $b > 5.2$ (Ludwig *et al.* 1978).

On increasing f (figure 2), the system passes through the bifurcation from high to low solutions for P . In this case the triple valued region is quite narrow, so we take a single value, $f_{\text{crit}} = 0.4$, to define this part of parameter space. For $f > f_{\text{crit}}$, the system will have very low yields compared with the high yields for $f < f_{\text{crit}}$.

For simplicity, consider a spatially uniform environment with effort $2\bar{f}$, split into halves, where different fishing efforts, f_1 and f_2 , are applied to the populations, P_1 and P_2 , in each half, with the constraint that the total effort $2\bar{f} = f_1 + f_2$ is fixed. Then the total yield

$$Y_{\text{tot}} = f_1 P_1 + f_2 P_2$$

is the total fishery yield and provides the critical test of the consequences of imposing some restrictions on fishing, f_1 , in one half, with a corresponding increase in the other half.

By defining k as the mixing or exchange rate of individuals between P_1 and P_2 , the system at equilibrium is described by

$$\frac{dP_i}{dt} = P_i \left(1 - \frac{P_i}{b} \right) - \frac{cP_i^2}{1 + P_i^2} - f_i P_i + k(P_j - P_i) = 0$$

for $i = 1, 2; j = 2, 1.$ (2.4)

Consider, first, the simplest situation, replacing the s-shaped terms with linear mortality, mP_i , and an exchange rate k , of zero. This corresponds to a system described by

Figure 1. Annual yield (in kilotonnes) versus fishing mortality for Georges Bank haddock, with a model for switching between different equilibria. Squares, 1931–1970; triangles, 1971–2000. (Adapted from Spencer & Collie 1997b.)

Figure 2. Growth minus fishing ($P(1 - P/b) - fP$) for three values of f ; plotted with the predation mortality (dot-dashed line) term $P^2/(1 + P^2)$.

equation (2.2), which has a maximum yield with $f_1 = f_2 = \bar{f}$. In general, for fixed $\bar{f}$, any yield Y_{tot} with $f_1 \neq f_2$ is less than Y_{av} , the yield with $f_1 = f_2$.

Now consider an extension of equation (2.2) to the case where $k > 0$. With overfishing defined by $0.5 < \bar{f} + m < 1$, let $\bar{f} = 0.5$ and $m = 0.25$, then figure 3a shows that for $f_1 = 0.25$ and $f_2 = 0.75$, Y_{tot} increases with an increase in k up to a maximum at $k_{\text{opt}} = 0.61$ and then decreases slowly towards Y_{av} . The maximum increase in yield is *ca.* 4%. Thus, with the traditional Schaefer model of an over-exploited fishery, introducing an MPA without decreasing overall effort may provide some slight benefit to the fishery, but could give large losses with slowly dispersing species.

If linear mortality is replaced by nonlinear mortality as described by equations (2.3) and (2.4), then for overfishing effort in the range of $f_{\text{crit}} < \bar{f} < 2f_{\text{crit}}$ it is possible to choose values of $f_1 < f_{\text{crit}}$ and $f_2 > f_{\text{crit}}$ constrained by $f_1 + f_2 = 2\bar{f}$ that satisfy $Y_{\text{tot}} > Y_{\text{av}}$.

For example, by taking the average effort $\bar{f} = 0.5 (> f_{\text{crit}})$ we can determine Y_{tot} as a function of k for various values

Figure 3. Total yield as a function of mixing rate, k with and without an MPA ($f_1 = f_2 = 0.5$); (a) with linear mortality only ($m = 0.25$); (b) with nonlinear mortality for several values of f_1 and f_2 . The dotted lines represent the regions of instability.

of f_1 and f_2 (figure 3b). Decreasing f_1 , corresponding to a progressively more protected fishing area, results in a decrease in yield at low exchange rates but an increased yield over a wider range of k . In all cases as $k \rightarrow \infty$, Y_{tot} reaches a maximum of Y_{max} , before decreasing rapidly to Y_{av} . For smaller values of f_1 the system bifurcates in a manner similar to the original spatially uniform model (figure 2).

The most striking example is obtained by imposing zero fishing, $f_1 = 0$, in the MPA half (a 'no-go' area). With $k = 0$ and $f_2 = 1.0$, the only solution to equation (2.3) is $P = 0$, giving $Y_{\text{tot}} = 0$. As mixing, k , is increased (figure 3b) a value of $Y_{\text{max}} = 2.6$ is reached for $k_{\text{opt}} = 0.66$. So within the constraints of this model, the overall maximum yield—more than four times Y_{av} —is obtained with $f_1 = 0$, $f_2 = 1.0$ for a dispersion rate of k_{opt} . It should be noted, however, that this optimal solution with a completely closed MPA is constrained by both minimum and maximum dispersion rates for this particular population. Less extreme pairs of f_1 and f_2 give lower Y_{max} but have a greater tolerance for low mixing rates.

Figure 4. Temporal development of total yield with a protected area compared to no protected area; for two mixing rates (1) low, $k = 0.1$; and (2) optimum, $k = 0.6$.

The time sequence in yield following a change in effort allocation creates problems for fishery managers. Figure 4 shows the yield with complete closure of half of the area and two mixing rates, low and optimum. For the low mixing rate, there is a decrease in yield for the first 7 years. In both cases, it can take 10–20 years for significant returns. This would be a major constraint for managers in addition to the usual effects of stochastic variations (Steele & Henderson 1984). The fishing mortality rates used in this model ($0.2\text{--}0.6\text{ years}^{-1}$) are of the same order as those for the Georges Bank haddock (figure 1). Thus, the lack of response to closures in this area a decade ago may not be unexpected.

3. DISCUSSION

For the traditional fishery model, equation (2.2), there is no significant advantage to the fishery in MPAs and the merits of MPAs must rest mainly on the impacts of fishing on the nontarget species (Hastings & Botsford 1999). With this simple model, the main threat to overfished stocks comes from fluctuations in effort or population growth near $f = 1.0$ that can drive the population to extinction. The advantage—as well as the problem—in the low-population ASS domain is stability in the face of small perturbations. This may be why many stocks are at ‘commercial’ rather than actual extinction. One rationale for MPAs—conserving breeding stocks of exploited species—may be more complicated in an ecosystem with ASSs (Thompson 1991).

Values derived from simulations using the ASS model are necessarily limited in their exact application. However, the general principle should hold that overfished systems with ASSs could obtain significantly increased yields with nonuniform distribution of fishing effort. The concept of ASS has potential application in coral reefs (Knowlton 1992) and in terrestrial and freshwater ecosystems (Scheffer *et al.* 2001) where there are corresponding concerns about the uses of reserves in regimes suffering from over-exploitation, and where these ideas would be applicable.

There are, as always, caveats about the relevance of simple models to complex ecological and technological issues. This model apparently for one population, P , is implicitly embedded in a food web whose other components determine the functional relationships for growth, natural predation and fishing mortality. It can be shown (Steele & Henderson 1981) that the same general switches occur when the predator is specified as an independent variable. Also it is assumed here that the ‘predator’ has the same density in the two halves.

More generally, the jury is still out on how far the ASS approach is a necessary as well as a sufficient explanation for the observed large amplitude changes in abundance. For example, the change from high to low abundance in Georges Bank haddock (figure 1) can be explained in terms of a large decrease in the effective growth rate, a , in equation (2.1) attributable perhaps to some climatic change (Spencer & Collie 1997b). These alternative explanations are a major concern to management generally as well as being critical in terms of benefits from the use of MPAs.

For MPAs, there is much more at stake than maximizing fishery yield for a given effort. The major thrust behind MPAs is the protection of those other components of the ecosystem that suffer from impact of fishing gear (NRC 2002). For fishing gear operating on the seabed, it is likely that the first few trawls do all the damage, therefore doubling the effort in part of the area does little more harm, whereas eliminating impact altogether within an MPA can have a very marked positive result. Thus, redistribution could be positive for nontarget communities as well as commercial fish stocks.

All of this is based on the presupposition that it is extremely difficult to alter the social and economic structure of the fishery. This is certainly true, and so it is useful to consider the possible uses of MPAs in this context. However, one must point out that decreasing the total fishing effort is still by far the optimal process for the fishery and the ecosystem. In terms of the model used here with its ASSs; if the total effort is reduced by 40% (from $2\bar{f} = 1.0$ to 0.6), then yield increases by more than five-fold ($Y_{\text{tot}} = 3.07$), significantly more than with the optimum mixing rate (figure 3). Even more significant, the catch per unit effort is eight times that of the original average rate. It is also twice the maximum rate with a no-go area and optimal dispersion of the stock. Thus, the advantages derived from MPAs are outweighed by those obtained with effort reduction. Any management strategy involving MPAs needs to include ways to reduce effort or capacity.

4. CONCLUSION

The existence of ASSs in marine ecosystems can be a critical issue in determining the potential value of MPAs. Given possible ‘regime shifts’ resulting from overfishing and given the social problems inherent in reducing capacity in many fisheries, MPAs can play a part in increasing yield and conserving nontarget communities. But such a strategy is second best, ecologically and economically, compared with effort or capacity reduction.

Acknowledgements

Both authors acknowledge support from the National Oceanic and Atmospheric Administration through the Cooperative Institute for Climatic and Ocean Research Award no. NA17RJ1223. The authors thank J. Collie for the provision of data and advice. Woods Hole Oceanographic Institution contribution no. 10965.

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