Ecology Letters, (1998) 1 : 87–90

LETTER

No-take areas for sustainability of harvested species and a conservation invariant for marine reserves

Marc Mangel
Department of Environmental Studies and Institute of Marine Sciences, University of California, Santa Cruz, CA 95064, U.S.A.
E-mail: msmangel@cats.ucsc.edu

Abstract

Various kinds of no-take areas (refuges, reserves) are gaining attention as conservation tools. The efficacy of reserves can be considered from the perspectives of providing baseline data sets, protecting the stock, maximizing yield to the fishery, or some combination of these. Regardless of the measure of effectiveness of a reserve, practical application requires the development of techniques for settling operational and policy questions such as how large a reserve should be. A simple model, involving population growth and harvest, is used to explore how the fraction of habitat assigned to a reserve affects the sustainability of a take and to frame the trade-off between control of harvest outside of the reserve and the size of the reserve. This exploration also leads to the discovery of a robust conservation invariant for reserves.

Keywords

Invariants, marine protected areas, marine reserves, sustainable fisheries.

Ecology Letters (1998) 1 : 87–90

INTRODUCTION

No-take areas (refuges, reserves) are increasing in visibility as conservation and management tools (e.g. Carr & Reed 1993; Gubbary 1995; Shackell & Willison 1995; Bohnsack & Ault 1996). Sound scientific advice to those involved with legislation and decision-making concerning reserves must include information on the size of the reserve and often must be provided in the face of considerable biological and operational uncertainty. In such circumstances, a tool for policy analysis should be robust to alternative assumptions. Consistent with a precautionary approach (Bodansky 1991; Costanza & Cornwell 1992; Dovers & Handmer 1995), a conservative estimate of reserve size is most likely to be appropriate. Finally, because recent legislation in the US focuses on the sustainability of fisheries (104th Congress of the United States of America 1996), it is important to know if reserves or no-take areas can improve the prospects for sustainability.

MATERIALS, METHODS, AND RESULTS

Envision a population that grows according to logistic stock dynamics,

$$N(t+1) = N(t) + rN(t)\left[1 - \frac{N(t)}{K}\right] \quad (1)$$

where $N(t)$ is the size of the population at the start of year t, before either take or reproduction, r is the maximum per capita reproductive rate, and K is the carrying capacity of the habitat. The choice of growth dynamics in eqn 1 is not crucial for the development that follows, but allows some analytical simplification. Logistic dynamics or their generalization fit a wide variety of species, from barnacles (Roughgarden *et al.* 1994) to whales (Clark 1985), and do so because of the logical simplicity: when population size is small [so that $N(t)/K << 1$] the population grows proportional to its size; when the population is larger growth slows. Although eqn 1 is based on the assumption of a closed population, this is not crucial for the analysis that follows.

Creating a no-take reserve means that some fraction A of the habitat is set aside and that harvest does not occur in the reserve. In the remaining part of the habitat, harvest (take) occurs and a fraction u of the population there is removed. In most harvesting operations, the precise value of the harvest fraction is not known; the sources of this uncertainty include lack of controllability of effort, natural fluctuations, incidental mortality, and/or illegal take (Milner-Gulland & Leader-Williams 1992; Leader-Williams & Milner-Gulland 1993; Mangel 1993; Alverson *et al.* 1994; Gillis *et al.* 1995a, b; Hart 1997). Regardless of the source of uncertainty, one can assume that the take can be bounded by a maximum value u_{max}, which in the extreme case could be as large as 1 (Nowliss & Roberts 1998). A specific alternative in which the harvest fraction is targeted but varies stochastically is considered by Lauck *et al.* (1998); their results could be combined with the approach described here. By working with the maximum value of take, one implicitly accepts that some kinds of harvest mortality, such as incidental by-catch and discard, will never really be known (Gillis *et al.* 1995a, b; Gunderson 1997), and that effective management should not only recognize this lack of certainty but embrace it as part of the planning (Mangel *et al.* 1996).

If reproduction follows take, the population size after take, but before reproduction is $AN(t) + (1-A)(1-u)N(t) = (1-u+Au)N(t)$. Consequently, in a year in which the take is u, the population dynamics are

$$N(t+1) = (1-u+Au)N(t) + r(1-u+Au)N(t)\times$$
$$\times\left[1 - \frac{(1-u+Au)N(t)}{K}\right] \qquad (2)$$

The steady state population size, found by setting $N(t) = N(t+1) = \overline{N}(u)$, is given by

$$\overline{N}(u) = \frac{K}{1-u+Au}\left[1 - \frac{u(1-A)}{r(1-u+Au)}\right] \qquad (3)$$

and the steady state yield is $Y(u) = u(1-A)\overline{N}(u)$.

Since u is bounded by u_{max}, the minimum reserve fraction needed to ensure sustainability of the population at a fraction f of the carrying capacity is the value of A that makes $\overline{N}(u)/K = f$ when $u = u_{max}$. This value is the larger of 0 or

$$A_r(f) = 1 +$$
$$\frac{1 + r - 2rf - \sqrt{(1+r-2rf)^2 - 4r^2 f(f-1)}}{2rfu_{max}} \qquad (4)$$

When $f = 0$, eqn 4 simplifies and gives the minimum value of the reserve fraction to ensure that the population persists

$$A_r(0) = \frac{u_{max}(r+1) - r}{u_{max}(r+1)} \qquad (5)$$

If $u_{max} < r/(r+1)$ then the minimum reserve size required to guarantee persistence is 0; otherwise it is greater than 0 (Fig. 1).

The steady population level given by eqn 3 and steady state yield $Y = u_{max}(1-A)N$ involves the combination of parameters $I = u_{max}(1-A)$. This combination is thus a no-take invariant, in the sense that similar results are obtained regardless of the individual values of u_{max} and A, as long as I is constant. Invariants have a long and rich contribution to fishery science (Beverton 1992; Charnov 1993; Mangel 1996), so it is not completely remarkable that another one arises here. In terms of this invariant, the steady state population size is

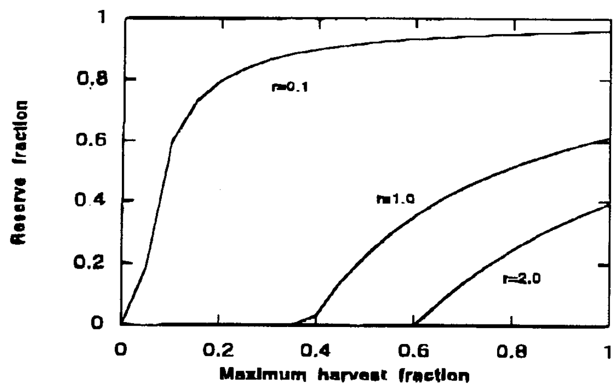

Figure 1 Reserve fraction, predicted by eqn 4, for populations in which maximum per capita growth rate is 0.1, 1.0, or 2.0 and $f = 0.6$.

$$\overline{N}(I) = \frac{K}{1-I}\left[1 - \frac{I}{r(1-I)}\right] \qquad (6)$$

The maximum value of I consistent with sustainability of the stock at a fraction f of carrying capacity is

$$I_r(f) =$$
$$\frac{-(1+r-2rf) + \sqrt{(1+r-2rf)^2 - 4r^2 f(f-1)}}{2rf} \qquad (7)$$

Because the steady state yield is

$$Y(I) = I\overline{N}(I) = \frac{IK}{1-I}\left[1 - \frac{I}{r(1-I)}\right] \qquad (8)$$

it is possible to find the value of the invariant that maximizes yield, for each value of r, consistent with the population being sustained at a level fK (Fig. 2). This figure demonstrates that commercial fisheries and stock conservation may be able to operate positively together. That is, if per capita growth rate is sufficiently high, the optimal level of yield for stock protection occurs at a reserve size that is larger than that for stock persistence at a specified fraction of carrying capacity.

DISCUSSION

No-take areas have been proposed for ground fish, reef fish, mollusks, crustaceans, and echinoderms (Bohnsack 1992; Dugan & Davis 1993; Auster & Shackell 1997), but design considerations for marine reserves are still developing. Although some ideas from terrestrial reserve design may be helpful in the determination of marine reserves, the primary concern to fishery management is

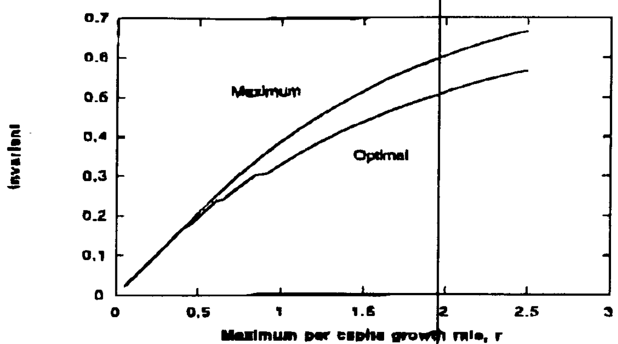

Figure 2 Maximum and optimal values of the invariant $I = u_{max}(1-A)$ as a function of maximum per capita growth rate when $f = 0.6$. The maximum value of the invariant is the value that ensures that the population level is fK. The optimal value is the one that maximizes the yield, given by eqn 8.

determining the level of protection required to maintain the fishery (Carr & Reed 1993). To enhance, preserve, and stabilize fisheries, reserves must provide production of target species (Dugan & Davis 1993). The results presented here show how reserves can be used to achieve the combined goals of sustaining fishery yields and protecting stocks. They also allow us to explore the trade-off between regulation of harvest outside of the reserve and reserve size. Although the size of reserves required by slowly growing species is large if the take is relatively uncontrollable (i.e. u_{max} is close to 1), the theory of reserves developed in this paper allows one to make informed choices about how large the reserve needs to be. The no-take fraction of the habitat predicted in this manner thus depends strongly on what happens in the fishery outside of the no-take zone as well as the biological dynamics within the reserve. The assumption of perfect mixing of individuals from the take and no-take portions of the habitat at the time of reproduction is a simple null model for the transfer function that connects dispersal rates and interception rates, recruitment, and the population dynamics of adults. Alternatives may change the quantitative details of the results, but are not likely to change the qualitative patterns. Consistent with a precautionary approach, the predicted reserve is conservative, because it is based on the assumption that the take will always be at its maximum value [alternatives are considered in Lauck *et al.* (1998) in which takes fluctuate around a targeted value]. The invariant $I = u_{max}(1-A)$ is a robust feature of the model and provides a general rule of thumb for the determination of the size of reserves in the face of uncertainty about what happens outside of the reserve.

ACKNOWLEDGEMENTS

The idea of using u_{max} is due to Josh Nowliss (Nowliss & Roberts, in press). I thank Melanie Bojanowski for comments, particularly on Fig. 2, and two anonymous referees for additional comments that helped clarify the manuscript. This paper is dedicated to the memory of Ray Beverton, who would have been delighted by the discovery of another invariant in fisheries science.

REFERENCES

104th Congress of the United States of America (1996). "Sustainable Fisheries Act" or Amended version of "Magnuson-Stevens Fishery Conservation and Management Act". *Public Law*, 94–265, Washington DC.

Alverson, D.L., Freeberg, M.H., Murawski, S.A. & Pope, J.G. (1994). *A Global Assessment of Fisheries Bycatch and Discards.* FAO Fisheries Technical Paper 339, Food and Agriculture Organization of the United Nations, Rome.

Auster, P.J. & Shackell, N.L. (1997). Fishery reserves. In *Northwest Atlantic Groundfish: Perspectives on a Fishery Collapse*, ed. J Boreman, B.S. Nakashima, J.A. Wilson, & R.L. Kendall. Bethesda, MD: American Fisheries Society, pp. 159–166

Beverton, R.H. (1992). Patterns of reproductive strategy parameters in some marine teleost fishes. *J. Fish Biol.*, 41 (Suppl. B), 137–160.

Bodansky, D. (1991). Scientific uncertainty and the precautionary principle. *Environment*, 33, 4+.

Bohnsack, J.A. (1992). Reef resource habitat protection: the forgotten factor from R.H. Stroud (ed.) Stemming the Tide of Coastal Fish Habitat Loss. *Mar. Recreational Fish*, 14, 117–129.

Bohnsack, J.A. & Ault, J. (1996). Management strategies to conserve marine biodiversity. *Oceanography*, 9, 73–82.

Carr, M.H. & Reed, D.C. (1993). Conceptual issues relevant to marine harvest refuges – examples from temperate reef fishes. *Can. J. Fish Aquat. Sci.*, 50, 2019–2028.

Charnov, E. (1993). *Life History Invariants.* New York: Oxford University Press.

Clark, C.W. (1985). *Bioeconomic Modelling and Fisheries Management.* New York: Wiley.

Costanza, R. & Cornwell, L. (1992). The 4P approach to dealing with scientific uncertainty. *Environment*, 34, 12+.

Dovers, S.R. & Handmer, J.W. (1995). Ignorance, the precautionary principle, and sustainability. *Ambio.*, 24, 92–97.

Dugan, J.E. & Davis, G.E. (1993). Applications of marine refugia to coastal fisheries management. *Can. J. Fish Aquat. Sci.*, 50, 2029–2042.

Gillis, D.M., Pikitch, E.K. & Peterman, R.M. (1995a) Dynamic discarding decisions – foraging theory for high-grading in a trawl fishery. *Behav. Ecol.*, 6, 146–154.

Gillis, D.M., Peterman, R.M. & Pikitch, E.K. (1995b) Implications of trip regulations for high grading – a model of the behavior of fisherman. *Can. J. Fish. Aquat. Sci.*, 52, 402–415.

Gubbary, S. (1995). *Marine Protected Areas: Principles and Techniques for Management.* London: Chapman and Hall.

Gunderson, D.R. (1997). Spatial patterns in the dynamics of slope rockfish stocks and their implications for management. *Fishery Bull.*, 95, 219–230.

Hart, P.J.B. (1997). Controlling illegal fishing in closed areas: the case of mackerel off Norway. In *Developing and Sustaining World Fisheries Resources. Proceedings of the 2nd World Fisheries Congress*, ed. D.A. Hancock, D.C. Smith, A. Grant and J.P. Beumer. Collingwood, Australia: CSIRO, pp. 411–414.
Lauck, T., Clark, C.W., Mangel, M. & Munro, G.R. (1998). Implementing the precautionary principle in fisheries management through marine reserves. *Ecol. Applications*, 8 (Suppl.), S72–S78.
Leader-Williams, N. & Milner-Gulland, E.J. (1993). Policies for the enforcement of wildlife laws-the balance between detection and penalties in Luangwa Valley, Zambia. *Conservation Biol.*, 7, 611–617.
Mangel, M. (1993). Effects of high-seas driftnet fisheries on the northern right whale dolphin *Lissodelphis borealis*. *Ecol. Applications*, 3, 221–229.
Mangel, M. (1996). Life history invariants, age at maturity and the ferox trout. *Evol Ecol.*, 10, 249–263.
Mangel, M., Talbot, L.M., Meffe, G.K. *et al.* (1996). Principles for the conservation of wild living resources. *Ecol. Applications*, 6, 338–362.
Milner-Gulland, E.J. & Leader-Williams, N. (1992). A model of incentives for the illegal exploitation of black rhinos and elephants – poaching pays in Luangwa Valley, Zambia. *J. Appl. Ecol.*, 29, 388–401.
Nowliss, J.S. & Roberts, C.M. (1998). Fisheries benefits and optimal design of marine reserves. *Fishery Bull.*, in press.
Roughgarden, J., Pennington, T. & Alexander, S. (1994). Dynamics of the Rocky intertidal zone with remarks on generalization in ecology. *Philosoph Transactions Royal Soc. London*, 343, 79–85.
Shackell, N.L. & Willison, J.H.M. (1995). *Marine Protected Areas and Sustainable Fisheries.* Wolfville, NS, Canada: Science and Management of Protected Areas Association.

BIOSKETCH

Marc Mangel is Professor in the Department of Environmental Studies and the Institute of Marine Sciences at the University of California, Santa Cruz. His research interests are focused on the ecological implications of life history variation. He has written *Decision and Control in Uncertain Resource Systems*, *Dynamic Modelling in Behavioural Ecology* (with Colin Clark) and *The Ecological Detective. Confronting Models with Data* (with Ray Hilborn).

Manuscript received 7 April 1998
First decision made 4 May 1998
Manuscript accepted 8 June 1998