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Bulletin of Mathematical Biology 67 (2005) 957–971

Bulletin of
Mathematical
Biology

www.elsevier.com/locate/ybulm

Marine reserves with ecological uncertainty

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Received 16 June 2004; accepted 11 November 2004

Abstract

To help manage the fluctuations inherent in fish populations scientists have argued for both an ecosystem approach to management and the greater use of marine reserves. Support for reserves includes empirical evidence that they can raise the spawning biomass and mean size of exploited populations, increase the abundance of species and, relative to reference sites, raise population density, biomass, fish size and diversity. By contrast, fishers often oppose the establishment and expansion of marine reserves and claim that reserves provide few, if any, economic payoffs. Using a stochastic optimal control model with two forms of ecological uncertainty we demonstrate that reserves create a resilience effect that allows for the population to recover faster, and can also raise the harvest immediately following a negative shock. The tradeoff of a larger reserve is a reduced harvest in the absence of a negative shock such that a reserve will never encompass the entire population if the goal is to maximize the economic returns from harvesting, and fishing is profitable. Under a wide range of parameter values with ecological uncertainty, and in the ‘worst case’ scenario for a reserve, we show that a marine reserve can increase the economic payoff to fishers even when the harvested population is *not* initially overexploited, harvesting is economically optimal and the population is persistent. Moreover, we show that the benefits of a reserve *cannot* be achieved by existing effort or output controls. Our results demonstrate that, in many cases, there is no tradeoff between the economic payoff of fishers and ecological benefits when a reserve is established at equal to, or *less* than, its optimum size.

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1. Introduction

Marine reserves remain controversial with fishers (Suman et al., 1999) despite their endorsement at the 2002 World Summit on Sustainable Development and empirical evidence that reserves can raise the spawning biomass and mean size of exploited populations within protected areas (Gell and Roberts, 2002; Halpern, 2003). The concerns of fishers are that establishment of reserves will (a) reduce (at least initially) their harvests and increase costs, (b) restrict when and where they can go fishing and, (c) depending upon their location, unduly penalize individuals who may be prohibited from operating in traditional fishing grounds (National Research Council, 2001). Moreover, placing reserves in inappropriate locations or creating reserves of an inappropriate size may generate lower payoffs than if traditional input or output controls are used (Holland and Brazee, 1996).

In this paper we develop a dynamic bioeconomic model to ascertain whether marine reserves can generate positive economic returns to fishers in a deterministic and a stochastic environment when harvesting is optimal. Our approach allows us to solve for a reserve size that maximizes the economic payoff from fishing, correct some widely held misconceptions about marine reserves and generate important insights into the benefits of marine reserves.

2. Theory

An understanding of source–sink dynamics (Pulliam, 1988) provides a key to understanding the benefits of marine reserves, as does the bioeconomic modeling of optimal harvesting (Roughgarden and Iwasa, 1986; Tuck and Possingham, 1994, 2000). We model a permanent reserve as a possible population source that creates a ‘no-take’ area for a proportion $s \in (0, 1)$ of the population. The growth functions of the population within the reserve, given by $f(x_R, s)$, and the harvested area, given by $f(x_{NR}, s)$, are defined as

$$f(x_R, s) = rx_R \left(1 - \frac{x_R}{sK}\right)^\alpha \quad (1)$$

$$f(x_{NR}, s) = rx_{NR} \left(1 - \frac{x_{NR}}{(1-s)K}\right)^\alpha \quad (2)$$

where x_R and x_{NR} are the population in the reserve and the harvested area, r is the intrinsic growth rate, K is the total population’s carrying capacity when there is no reserve and α is a parameter.

We deliberately construct the ‘worst case’ scenario for having a reserve such that we ignore all benefits, such as biodiversity conservation, habitat restoration, population persistence, avoidance of catastrophic ecosystem shifts, with the exception of spillovers to the fishery. We also model the problem so that harvesting is economically optimal despite the fact that management errors provide additional support for marine reserves (Lauck et al., 1998).

In our model the only goal is to maximize the discounted net returns from fishing where the per-period payoff is $\Pi(h, x_{NR}, s) = p(h)h - c(h, \frac{x_{NR}}{(1-s)K})$. We define h as total harvest, $p(h)$ as the market inverse demand function and $c(h, \frac{x_{NR}}{(1-s)K})$ as the aggregate cost

function that is increasing in the harvest and non-increasing in the population density of the harvested population.

Ecological uncertainty is modeled by two shocks: one, a shock that may be either positive or negative that represents *environmental stochasticity* due to temporal variation in the habitat (Shaffer, 1981) and, the other, a negative shock that may be of a small or large magnitude that occurs randomly over time due to temperature change, a pollution event or some other harmful occurrence. We model environmental stochasticity as a Wiener diffusion process (Brownian motion) that follows a normal distribution (W_t) and negative shocks as a jump process (q) that follows a Poisson distribution with parameter λ . Environmental sensitivity to a realization dW is given by $g(x_R)$ and $g(x_{NR})$ that represent the proportional effect of environmental stochasticity on the reserve and harvested populations. Sensitivity of the reserve and harvested population to a negative shock of magnitude dq is represented by the functions $\psi(x_R)$ and $\gamma(x_{NR})$ that differ to reflect the possibility that the effects of a negative shock may be greater in the fishery than the reserve.

The dynamic optimization problem for determining the optimal reserve size and harvest is

$$V(x_R, x_{NR}) = \max_h \int_0^\infty e^{-\rho t} \Pi(h, x_{NR}, s) dt \tag{3}$$

subject to

$$dx_R = \left[f(x_R, s) - \phi(1-s) \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) \right] dt + g(x_R)dW + \psi(x_R)dq \tag{4}$$

$$dx_{NR} = \left[f(x_{NR}, s) + \phi(1-s) \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) - h \right] dt + g(x_{NR})dW + \gamma(x_{NR})dq \tag{5}$$

$$x_0 = x(0) \tag{6}$$

where $V(x_R, x_{NR})$ is the value function, ρ is the discount rate, x_0 is the sum of the initial value of the population inside and outside of the reserve, ϕ is the transfer coefficient and $\phi(1-s) \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right)$ is the transfer function that governs migration to and from the reserve and possible spillovers to the fishery (Roberts et al., 2001). The transfer function is consistent with other models of diffusion in a fishery (Guénette and Pitcher, 1999; Kramer and Chapman, 1999) and implies that, for a given density difference between the reserve and fishery, the larger the reserve size, the lower the number of fish transferred.

Using Ito’s lemma, Bellman’s fundamental equation of optimality can be used to solve the problem specified by Eqs. (3)–(6) above for the harvest trajectory given the reserve size, i.e.,

$$\begin{aligned} \rho V(x_R, x_{NR}) = \max_h & \left[\Pi(h, x_{NR}, s) + V_{x_{NR}}(x) \left[f(x_{NR}, s) + \phi(1-s) \right. \right. \\ & \times \left. \left. \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) - h \right] \right. \\ & \left. + V_{x_R}(x) \left[f(x_R, s) - \phi(1-s) \left(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right) \right] \right] \end{aligned}$$

$$\begin{aligned}
 & + \frac{1}{2} V_{x_R x_R} g(x_R)^2 + \frac{1}{2} V_{x_{NR} x_{NR}} g(x_{NR})^2 + V_{x_R x_{NR}} g(x_R) g(x_{NR}) \\
 & + \lambda [V(x_R + \psi(x_R), x_{NR} + \gamma(x_{NR})) - V(x)] \Big) \tag{7}
 \end{aligned}$$

where the optimal harvest is determined from all possible reserve sizes to maximize an overall value function, defined by $V^*(x_R, x_{NR})$, for a given stochastic realization (dq and dW). Due to the complicated nature of the stochastic processes, Eq. (7) cannot be solved analytically. However, the economically optimal reserve size can be determined using a modified perturbation method (Judd, 1999) that we develop for this purpose for any set of parameter values. In our method of solution, we specify a constraint that the population transferred from reserve to fishery (or vice versa) cannot exceed the amount within each location.

The method that we develop to solve Eq. (7) involves introducing two auxiliary variables (one for a Brownian diffusion process and another for the jump process) defined as η and ε into the Bellman equation, where if $\eta = \varepsilon = 0$ the deterministic problem results. Following the substitution, the decision function and value function can be defined as $II(h, x_{NR}, s, \eta, \varepsilon)$ and $V(x_{NR}, x_R, \eta, \varepsilon)$, and an n th-order Taylor series expansion can be defined around the steady state in the deterministic case. In the first step we solve for the steady state in the deterministic case ($\eta = \varepsilon = 0$) by using the maximum condition for the Bellman equation, applying the envelope theorem and the equations of motion for the reserve and non-reserve populations. In the second step, we differentiate the maximum condition and envelope theorem equation with respect to the state variables x_R and x_{NR} . In step three, we differentiate the Bellman equation to find V_η and V_ε that are expressions of higher order derivatives with respect to the state variables found in step two. Successive differentiation of the Bellman equation with respect to the auxiliary variables, control variables and state variables allows us to solve with greater precision for required values in a grid-like pattern.

Our method of solution was automated using MAPLE to calculate the partial derivatives of the optimal value function and control variables with respect to the state and the auxiliary variables, and to solve for the optimal harvest levels for a given reserve size. The optimal reserve size, or the value of s that maximizes the sum of the discounted net returns from fishing, was found by selecting the harvest that generates the highest economic value from fishing for all possible reserve sizes. In practice, a fourth-order differentiation of the Bellman equation was applied and found sufficient, with regularity conditions requiring that the value and decision functions be differentiable with respect to the stock variable (Blume et al., 1982; Atakan, 2003). Simulated results verify that errors of approximation to first-order conditions are near zero.

3. Simulations

To illustrate the bioeconomic effects of marine reserves, we define the following demand and cost functions:

$$p(h) = ah^\varepsilon \tag{8}$$

$$c\left(h, \frac{x_{NR}}{(1-s)K}\right) = \frac{bh(1-s)K}{x_{NR}}. \quad (9)$$

We specify $a = b = 1.0$ and $\varepsilon = -0.3$ for our simulations and use the following values for the biological parameters: $r = 0.30$, $K = 1.0$ and $\alpha = 1.0$. We also define the initial population in the reserve and fishery as 1.0, the discount rate as 5% ($\rho = 0.05$) and the transfer coefficient as $\phi = 3.5$, which corresponds to a 10–15% transfer of the total fish in the reserve when $dq = 0$.

Environmental sensitivity is modeled by $g(x_R) = 0.01x_R$ and $g(x_{NR}) = 0.01x_{NR}$ for a random realization of -1 and $+1$. The probability of the negative shock is 0.10 in both the reserve and fishery and we consider a range of cases where $\psi(x_R) = \beta x_R$ and $\beta \in (-0.1, 0)$, with $\gamma(x_{NR}) = -0.1x_{NR}$. These parameters imply that a negative shock equal to a 10% reduction of the population in the fishery, and between 0 and 10% reduction in the reserve, occurs on average every 10 years. Both the probability and size of these negative shocks are conservative relative to the fluctuations that are common in many exploited fisheries (Caddy and Gulland, 1983; Hofmann and Powell, 1998; Ludwig et al., 1993).

3.1. Value functions with and without ecological uncertainty

Fig. 1 shows the value function or discounted net returns from fishing graphed against reserve size for the case of a constant environment ($dW = dq = 0$), but with optimal harvesting. The figure shows what was also found by Conrad (1999), namely, that with *no* ecological uncertainty and with optimal harvesting, a reserve generates no economic benefits to fishers. Such an outcome corresponds to the view of many fishers, and also some economists, that reserves are unnecessary and costly if input or output controls are used optimally (Hannesson, 1998; Anderson, 2002).

Although a reserve generates a negative economic payoff with a constant environment and optimal harvesting, this is *not* the case in the presence of ecological uncertainty. Indeed, we can readily show a robust result using parameter values consistent with real world conditions that a reserve of size $s > 0$ is economically beneficial with ecological uncertainty. Such a result is consistent with the view that with a fluctuating environment a reserve generates an extra payoff in terms of increased stability (Armsworth and Roughgarden, 2003). We illustrate that this result is independent of the initial population in Table 1. The table shows the value of the value function under different reserve sizes and initial values of the population for the case $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$. In particular, Table 1 indicates that the higher the initial population, the higher the value of the value function, but the optimal reserve size (50%) does not change with the initial population. Thus whether or not the population is initially overexploited has no impact on either the optimal size of the steady-state population or the optimal reserve size if harvesting is economically optimal.

Our finding is striking because it is obtained with optimal harvesting and occurs even when the harvested population is *not* overexploited. In other words, even if a fishery is optimally managed with knowledge as to the size and probability of environmental variability for maximizing the net returns from fishing, a marine reserve still generates a higher economic payoff than no reserve. Moreover, this result holds true even if the population is not initially overexploited and for a wide range of parameter values

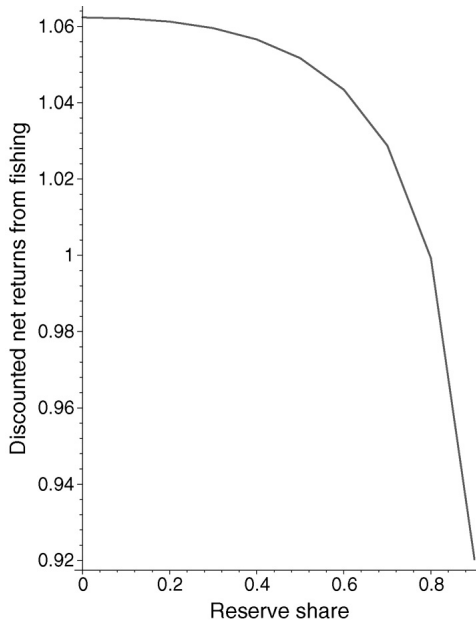


Fig. 1. Reserve size and discounted net returns from fishing with a constant environment ($x_0 = 0.5$).

Table 1
The value function for different reserve and initial population sizes

Initial population	Reserve size (s)									
	0	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
0.4	0.9489	0.9548	0.9602	0.9647	0.9680	0.9694	0.9677	0.9599	0.9383	0.8702
0.5	1.0005	1.0065	1.0119	1.0164	1.0196	1.0208	1.0186	1.0100	0.9864	0.9135
0.6	1.0476	1.0536	1.0590	1.0635	1.0665	1.0675	1.0649	1.0554	1.0301	0.9524
0.7	1.0911	1.0972	1.1026	1.1070	1.1099	1.1106	1.1075	1.0971	1.0700	0.9878
0.8	1.1317	1.1379	1.1432	1.1476	1.1504	1.1508	1.1472	1.1359	1.1070	1.0202
0.9	1.1701	1.1763	1.1816	1.1859	1.1886	1.1887	1.1845	1.1723	1.1416	1.0503

Notes:

1. Each cell represents the value of the value function for a given reserve size and initial population.
2. A higher initial population generates a higher value for the value function for a given reserve size.
3. The optimal reserve size, marked in bold ($s = 0.50$), is independent of the initial population.

whenever the shock sensitivity, or the proportional effect of a negative shock on the reserve population, is equal to or less than that for the harvested population, i.e., $|\beta| \leq 0.10$. Indeed, in some cases, even if the shock sensitivity is *greater* in the reserve than the fishery, a positive reserve size may still be beneficial to fishers. This outcome is shown in Fig. 2 where the relative magnitude of the shock sensitivity in the reserve (β) is graphed against

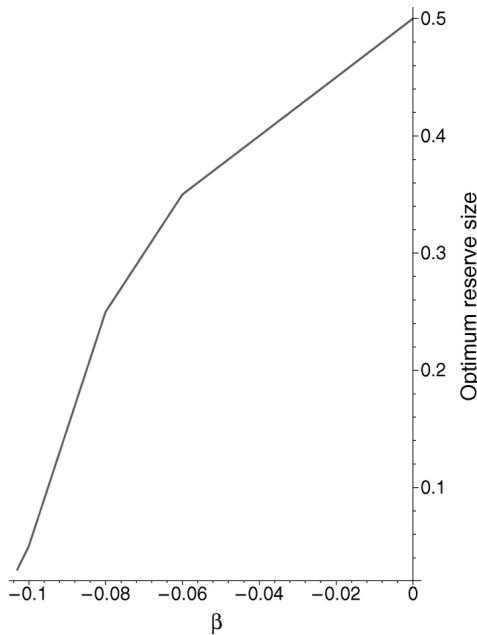


Fig. 2. The relationship between optimum reserve size and shock sensitivity of the reserve population.

optimal reserve size. In particular, Fig. 2 illustrates that there exist values of $|\beta| > 0.10$ where a reserve generates a positive economic payoff to fishers.

Table 2 provides further evidence of the economic payoff of reserves with ecological uncertainty. Each row uses a different parameter value for β that determines the shock sensitivity of the reserve population given that $\gamma(x_{NR}) = -0.10x_{NR}$. Thus the first row labeled 0.00 represents the case where $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.10x_{NR}$, the second row is the case where $\psi(x_R) = -0.02x_R$ and $\gamma(x_{NR}) = -0.10x_{NR}$, and so on until the last row is reached, where $\psi(x_R) = -0.10x_R$ and $\gamma(x_{NR}) = -0.10x_{NR}$. The columns represent different reserve sizes or values of s , and the cells are the discounted net returns from harvesting for a given β and s . For each row, the cell in bold corresponds to the reserve size closest to the optimum size.

Table 2 illustrates the following results. First, the economic payoff from fishing, whatever the reserve size, decreases as the shock sensitivity in the reserve becomes larger. Second, as illustrated in Fig. 2, optimal reserve size decreases as the shock sensitivity in the reserve becomes larger. Third, if it is optimal to have a reserve then, whatever the shock sensitivity, the economic payoff from fishing is concave in reserve size.

Our concavity result implies that if it is optimal to have a reserve, any marginal increase in reserve size when less than the optimum will increase the economic payoff to fishers while also generating potential environmental benefits, such as enhanced biodiversity conservation, habitat restoration, population persistence. In other words, if $s > 0$ is optimal, then there exists a continuum or gradient of reserve sizes that are smaller than the optimum size, but across which there is no tradeoff between ecological and economic

Table 2
The value function for different shock sensitivities and reserve sizes

β	Reserve size (s)											
	0	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55
0.00	1.00055	1.00360	1.00652	1.00929	1.01188	1.01425	1.01636	1.01815	1.01956	1.02047	1.02076	1.02023
-0.02	1.00055	1.00301	1.00534	1.00751	1.00951	1.01129	1.01282	1.01404	1.01487	1.01521	1.01494	1.01387
-0.04	1.00055	1.00241	1.00415	1.00574	1.00714	1.00834	1.00928	1.00991	1.01016	1.00994	1.00911	1.00748
-0.06	1.00055	1.00182	1.00297	1.00396	1.00477	1.00538	1.00573	1.00578	1.00545	1.00466	1.00326	1.00108
-0.08	1.00055	1.00123	1.00178	1.00218	1.00240	1.00242	1.00218	1.00164	1.00073	0.99936	0.99739	0.99466
-0.10	1.00055	1.00064	1.00059	1.00040	1.00003	0.99945	0.99862	0.99750	0.99600	0.99405	0.99151	0.98821

Notes:

1. β is the shock sensitivity of the reserve population following the realization dq .
2. In all cases the shock sensitivity of the harvested population is $\gamma(x_{NR}) = -0.10x_{NR}$ following the realization dq .
3. Cells in bold type are the discounted net returns from fishing at the optimal reserve size, for a given β .

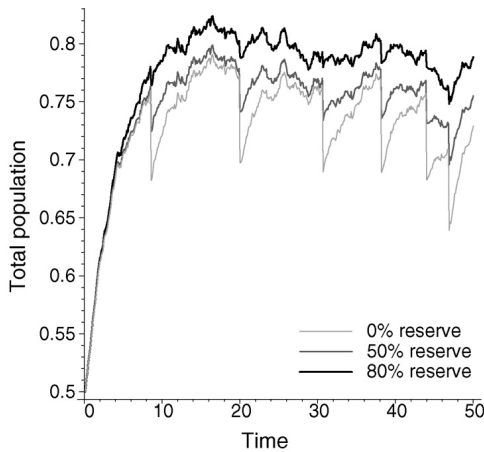


Fig. 3. The relationship between total population and reserve size ($x_0 = 0.5$).

benefits. This novel and general result is an example of a ‘win–win’ rarely found in resource management where increasing the economic payoff from harvesting is also consistent with an increase in ecosystem benefits. Moreover, with ecological uncertainty, the economic benefits that a reserve generates cannot be obtained from either effort or output controls, even when such controls are set optimally.

3.2. Resilience

The payoff of reserves to fishers with ecological uncertainty arises from what we call a ‘resilience effect’. This is defined as the time that it takes for the population to return to close to its former level before a shock (Pimm, 1984), whereby the recovery time is reduced with increasing reserve size. This resilience effect is not confined to the parameter values that we use, is *not* the same as population persistence as it occurs even when the population is not subject to extinction, and will *always* occur if the shock sensitivity in the reserve is equal to or less than that in the harvested population.

A greater population density in the reserve allows for a transfer of fish to the harvested area. This, in turn, reduces the recovery time of the harvested population and also permits fishers to harvest at a higher rate immediately after a negative shock than they would otherwise. Although the spillover or transfer can increase with reserve size, the cost of a larger reserve is a reduced harvest in the absence of a negative shock. As a result, a reserve will never encompass the entire population if the goal is to maximize the economic returns from harvesting and fishing is profitable. This is because, eventually, the marginal benefit or spillover from a slightly larger reserve with a negative shock will equal the marginal cost from harvesting foregone from a smaller sized fishery in the absence of a negative shock. The point at which the benefit and the cost from a marginal change in reserve size are equal is the optimum reserve size.

Fig. 3 illustrates resilience effects for three different reserve sizes ($s = 0, 0.50$ and 0.80) for the case $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$ and where the total population is graphed

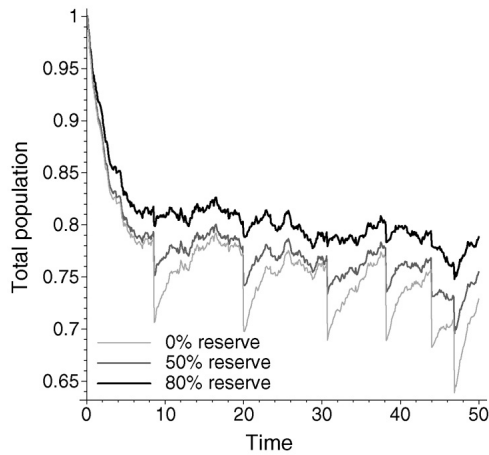


Fig. 4. The relationship between total population and reserve size ($x_0 = 1$).

against time. In the figure the few, but large, declines in the total population represent negative shocks and the small and irregular fluctuations over much smaller time intervals are environmental stochasticity. The figure clearly shows that the larger the reserve, the shorter the time it takes for the total (and also the harvested) population to recover from a negative shock. Fig. 4 shows that the steady-state population is the same as that in Fig. 3 even if the initial population is much larger.

The reason that a reserve generates an economic payoff, even with optimal harvesting, is shown in Fig. 5 for the case $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$. This figure graphs the harvest level against time for three different reserve sizes ($s = 0, 0.50$ and 0.80). Unlike Figs. 3 and 4 where a larger reserve always increases resilience, a larger reserve does not necessarily increase the average harvest. Indeed, a reserve size $s = 0.50$ generates a higher average harvest than $s = 0.80$. This is because although a larger reserve increases spillovers to the fishery, it also reduces the proportion of the population subject to harvesting. Thus, beyond some reserve size, and for a given level of environmental variability, further increases in the reserve reduce the average harvest. Fig. 6 shows that the steady-state harvest is the same for a different, and much larger, initial population.

3.3. Biological parameters

The resilience of a population for rebounding following a negative shock and for generating spillovers in the fishery is, in part, determined by its intrinsic growth rate and the dispersal ability and movement patterns of fish. The higher the intrinsic growth rate (r) at any reserve size, the quicker the population can recover following a shock. Consequently, the higher the intrinsic growth rate, the smaller the optimal reserve size. This result is shown in Fig. 7 for the case $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$. By contrast, the greater the transfer rate of fish from the reserve to the harvested area, the smaller the degree of protection provided by a reserve of a given size. In other words, the larger the transfer

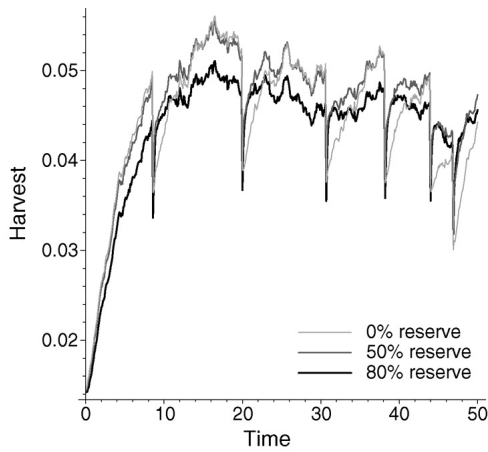


Fig. 5. Harvest against time ($x_0 = 0.5$).

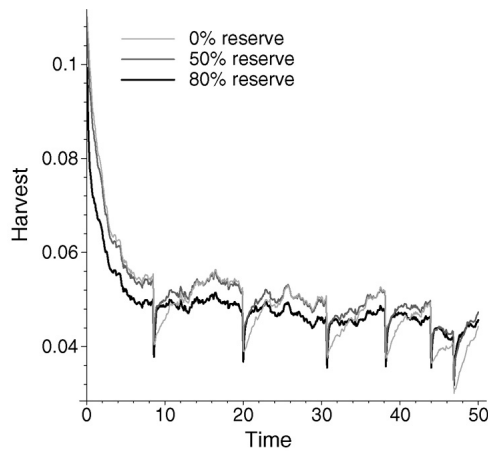


Fig. 6. Harvest against time ($x_0 = 1$).

coefficient (ϕ), the larger the optimal reserve size, as illustrated in Fig. 8 for the case $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$.

3.4. Discount rate

Finally, we observe that an increase in the discount rate (ρ) will reduce the economically optimal reserve size. This is because although the resilience effect generates an economic value to harvesters, it only does so to the extent that future returns are valuable. For our parameter values with $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$ an economically optimal reserve size still exists at a discount rate of 90% ($\rho = 0.9$), and with $\psi(x_R) = -0.1x_R$

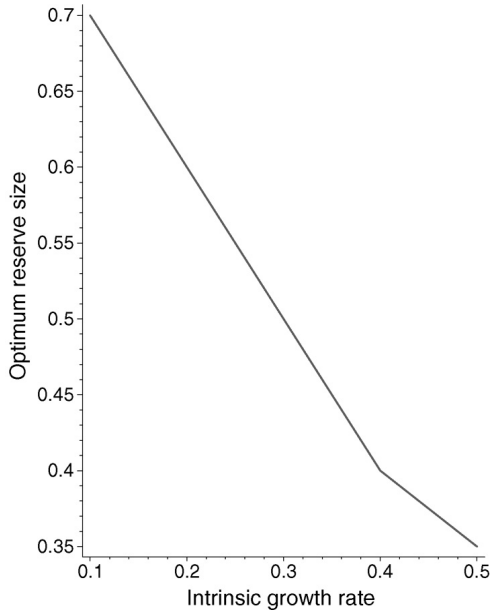


Fig. 7. The intrinsic growth rate and optimal reserve size.

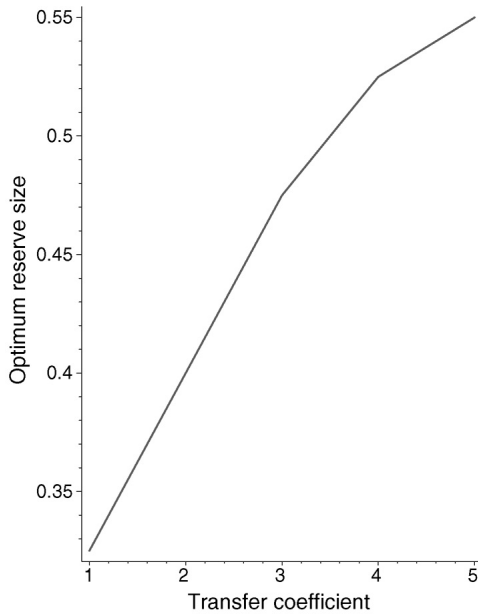


Fig. 8. The transfer coefficient and optimal reserve size.

and $\gamma(x_{NR}) = -0.1x_{NR}$ a reserve generates a positive economic payoff at any discount rate less than 25% ($\rho = 0.25$).

4. Discussion

The principal point of our study is that, for a wide range of parameter values and hence real world conditions, marine reserves can simultaneously generate benefits to both fishers and the environment. Our work complements existing studies on reserve size and design (Roberts et al., 2003). However, our results also go beyond the literature that shows reserves have value with ecological uncertainty because they can increase population persistence (Lauck et al., 1998; Sumaila, 1998), reduce the variance of the exploited populations (Conrad, 1999) and lower the variance in harvests (Sladek Nowlis and Roberts, 1998; Hannesson, 2002).

By incorporating ecological uncertainty into a bioeconomic model, and solving for optimal reserve size, we find that reserves are beneficial even with harvesting that tries to maximize the net returns from fishing. Our findings are noteworthy because they contradict widely held, but incorrect, views about reserves—namely, that for reserves to be beneficial to fishers, the population must be overexploited (Pezzey et al., 2000), reserves must be large (Anderson, 2002) and that reserves and output controls are equivalent methods in terms of their effects on fishery yields (Hastings and Botsford, 1999; Botsford et al., 2003).

Our results are of particular interest to fishery managers, but several caveats are required before applying our model to actual fisheries and when drawing inferences for real ecosystems. First, catastrophic shifts can and do occur in ecosystems and sustainable management of fisheries requires more than specifying a given reserve size for a population; it also demands a minimum population size to reduce the possibility of crossing undesirable population thresholds (Scheffer et al., 2001). Second, only small amounts of migration of fish may be required to generate broad-scale ‘phase synchronization’ that can generate chaotic peak abundances, but can also increase population persistence (Blasius et al., 1999). Third, reserves should be viewed as complementary to other management controls that may also help maintain or enhance yields (De Martini, 1993). Fourth, many fishery managers currently lack the information about transfer rates and spillovers between potential reserves and harvest areas needed for precisely determining optimal reserve size without further data collection (Holland, 2002).

5. Conclusions

The paper addresses the claim by fishers that marine reserves generate few, if any, economic payoffs. Using a bioeconomic model, we develop a framework that can be used to determine optimal reserve size. We show that with ecological uncertainty, marine reserves increase the economic returns to fishers for a wide range of parameter values.

Given the poor record of effort and output controls in sustaining fish stocks in the face of ecological uncertainty (Ludwig et al., 1993; Pauly et al., 2002), our results suggest that much of the resistance to reserves by fishers is misplaced. Indeed, in many fisheries,

our findings suggest that reserves can generate a ‘win–win’ situation for fishers and the environment.

Acknowledgements

We thank Pham Van Ha for his valuable research assistance and Rob Heinsohn and Jack Pezzey for insightful comments on earlier drafts. We are also grateful for the helpful comments of a referee.

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