Saving the seas: the economic justification for marine reserves

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Saving the Seas:
The Economic Justification for Marine Reserves

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ABSTRACT

We contribute to the understanding of marine reserves and the management of renewable resources with uncertainty. We show that the key benefit of reserves is that they increase resilience, or the speed it takes a population to return to a former state following a negative shock. Resilience can also increase resource rents even with optimal harvesting. We contradict the accepted wisdom that reserves have no value if harvesting is optimal, reserves and optimal output controls are equivalent, reserves have value only with overexploited populations and that reserves must be large to offer benefits to fishers.

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1. INTRODUCTION

A decade ago there were over 1300 marine reserves worldwide, with a median size of almost 1600 hectares (Kelleher *et al.* 1995), but many more reserves are planned (Botsford *et al.* 1997, Malakoff 1997). The proposed expansion of reserves, where no harvesting occurs, and protected areas, where some harvesting may be permitted, goes far beyond traditional no-take areas for spawning or nursery grounds. It also includes the agreement by national governments at the 2002 World Summit on Sustainable Development (WSSD) to develop representative networks of marine protected areas by 2012.[1] Under some proposals, marine protected areas could increase from just 0.4 percent of the area in the coastal US (Lindholm and Barr 2001) and less than 1 percent of the earth's oceans (Boersma and Parrish 1999) to upwards of 20 percent or more of marine coastal areas.[2] If this commitment is achieved, it will represent the largest ever transformation in the use (or rather non-use) of the earth's surface.

In this paper we address the economic question regarding reserves: what is their optimal economic size, taking into account both the sustainability of the resource and net returns from harvesting? We answer this question by developing a stochastic bioeconomic model that includes two forms of uncertainty (a continuous diffusion process and a jump process) with optimal harvesting. Such an approach is required because deterministic models that are common in the existing economics literature cannot show the effect of reserves on population resilience.[3]

By explicitly accounting for uncertainty and solving for the optimal harvest levels and reserve size using a perturbation method, we find that the economic benefits of reserves are understated in deterministic models. We also show that the value function is concave with respect to optimal reserve size. These results have important implications for the multi-billion dollar fishing industry, namely, that a reserve less than positive optimal size can generate higher economic benefits than no reserve even with optimal harvesting, risk neutrality and a persistent population. Our findings also provide a number of general 'rules of thumb' when establishing or enlarging reserves. Such rules are important and of immediate value given the data challenges required to determine optimal reserve size.

The following section reviews the existing literature and insights of both biological and economic models of reserves. Section three outlines the bioeconomic model and method we use to solve for an optimal reserve size. Section four uses specific parameters to analyze the effects of

biological and economic variables on reserve size, given optimal harvesting. Section five explores the insights of the model in terms of the establishment of reserves, while concluding remarks are offered in section six.

2. THE BIOECONOMICS OF RESERVES

The benefits of reserves are assessed from the perspective of spillovers to harvested areas, economic models of reserves, the importance of negative shocks on the value of reserves and our own economic justification for reserves.

Spillovers from Reserves

For the vast majority of exploited marine populations, perfectly enforced reserves reduce fishing mortality. This can generate positive harvesting spillovers to surrounding exploited areas, even for species that are sedentary as adults (such as shellfish), because a no-take area allows for spillovers if juveniles, larvae or eggs migrate beyond reserve boundaries. Thus reserves help create a source-sink dynamic whereby protected individuals are afforded a measure of protection in a given location, and can then act as a 'source' of recruitment for exploited areas outside of the reserve (Pulliam 1988).

Roberts *et al.* (2001), and others, show empirically that reserves can generate positive spillovers that improve harvests in adjacent exploited areas. Pezzey *et al.* (2000) and Sanchirico and Wilen (2001) also prove, in theoretical models with density-dependent growth, that a reserve can increase the abundance of the population and, in some cases, may even raise the aggregate harvest in the exploited area. This 'double payoff' arises when the chosen area for the reserve is at a low population level such that the marginal benefits of closure (reduced mortality, but with spillovers) outweigh its costs (loss of harvest in previously exploited area).

Economics Models of Reserves

One of the first economic models to examine the efficacy of reserves is Holland and Brazee (1996). Using a deterministic framework, they show that the relative benefits of reserves depend on their effects on harvesting in exploited areas and the discount rate. The greater is the short-term harvest loss through reserve creation and the greater the discount rate, the smaller are the benefits

of a reserve of a given size. In simulations, they also find that at higher fishing effort levels a correspondingly larger reserve size is required to generate greater discounted rents. Their work is also noteworthy for stressing the value of reserves as "insurance" to management failure, but emphasize that if effort (and harvests) can be perfectly controlled then reserves are of little or no value.

In subsequent work, Holland (2000) observes that a reserve can, in some cases, raise harvest and revenues if fishing effort is very high prior to the establishment of the reserve, although this could also be accomplished with more direct controls on fishing effort or harvest. Hannesson (1998) also uses a deterministic model and finds that reserves are redundant if the total catch can be perfectly controlled. He also shows that reserves would need to be in the order of 70-80 percent of a fishing area to yield benefits associated with an optimally controlled fishery and, to the extent that reserves initially reduce harvests in exploited areas, raise fishing costs and can exacerbate problems of overcapacity.

Sanchirico and Wilen (1999 and 2001) emphasize that establishing reserves will invariably change the level of fishing effort in exploited areas. How fishing effort redistributes after a reserve is established depends on the biology of the species, but also on the costs and returns of harvesting in different locations. Applying this idea to the California sea urchin fishery with a deterministic model, Smith and Wilen (2003) find that discounted rents *fall* with the creation of a reserve in heavily fished area if the spatial behavior of fishers is accounted for, but is predicted to rise if it is not. Thus the location of reserves requires both biological and economic understanding and their placement in, or near to, the most productive habitat need not necessarily be the best tactic (Sanchirico and Wilen 2002).

Negative Shocks and Reserves

An increase in the population size within the reserve has benefits beyond the spillovers in harvested areas (Roberts *et al.* 2001, Bhat 2003) because it raises the likelihood that the reserve population (and also the entire population because of transfers out of the reserve) will not be eliminated due to a catastrophe. Increased population persistence occurs because, for many negative shocks, the smaller is the population or the closer it approaches its minimum viable level from above, the greater is the chance of its elimination (Shaffer 1981).

By separating a population into exploited areas and reserves, the nature of the negative shocks to which species are subject to may be different, and may even be mitigated in reserves if the shocks are correlated with the level of harvesting. Consequently, reserves act as a hedge against irreducible uncertainty, especially shocks associated with the harvesting of exploited populations (Ludwig *et al.* 1993, Botsford *et al.* 1997) where harvest rates and population stocks are measured with error and harvests are less than fully controllable (Clark 1996).

Lauck *et al.* (1998) and Mangel (2000a) show that reserve size should increase with the size of the negative shocks to ensure population persistence. Sumaila (1998) and Mangel (1998) also demonstrate that the negative relationship between reserve size and the negative shocks in a fishery. Using the concept of an invariance kernel, Doyen and Béné (2003) find that the greater the level of uncertainty (size and/or probability of a negative shock), the greater the share of the population required in a reserve to maintain a minimum viable population. Conrad (1999) shows that, with no uncertainty, a reserve generates no direct harvesting benefits. He also finds that reserves can reduce the variation of the population while Sladek Nowlis and Roberts (1998), Mangel (2000b) and Hannesson (2002) all show that reserves can reduce the variation in the catch for a given size of the resource.

Economic Justification for Reserves

Those who incorporate stochasticity into their models show that reserves have value under uncertainty because they can increase population persistence and reduce the variance of populations and harvests. Until now, however, the full economic value of reserves under uncertainty has not been demonstrated. Using a dynamic source-sink model with two forms of uncertainty, we show that the key benefit of reserves is that they increase resilience, or the speed it takes a population to return to a former state following a negative shock. Increased resilience due to a reserve can also increase resource rents, even with optimal harvesting. Our findings contradict the prevailing wisdom that reserves have no value if harvesting is optimal, reserves only have value if the population is overexploited, they need to be of a very large size to offer benefits to fishers and that reserves and output controls are equivalent methods of managing fisheries.

3. A DYNAMIC SOURCE-SINK MODEL OF A RESERVE

To address the question of how reserve size for an exploited population may be calculated under a range of realistic scenarios, we need to explicitly model uncertainty and the regulations governing harvests. We assume that the population, without harvesting, is governed by density-dependent growth defined by

$$f(x) = rx(1 - \frac{x}{K})^\alpha \tag{1}$$

where x is the population or biomass, $f(x)$ is its growth, r is the intrinsic growth rate, α is a parameter and K is the carrying capacity of the given habitat.

The model assumes the population's value comes from its resource rents. It thus ignores the value of reserves in terms of biodiversity (Hastings and Botsford 2003) and precludes any additional value associated with population persistence. Inter-temporal rents from harvesting the population are defined by

$$\Pi(h, x_{NR}) = p(h)h - c(h, \frac{x_{NR}}{K}) \tag{2}$$

where h is harvest, x_{NR} is the population *not* in the reserve, $p(h)$ is the inverse demand function and $c(h, \frac{x_{NR}}{K})$ is the aggregate cost function where $c_1(h, \frac{x_{NR}}{K}) > 0$ and $c_2(h, \frac{x_{NR}}{K}) \leq 0$ such that costs rise with the harvest, but do not increase with population density.

In the case of a permanent reserve that protects proportion $s \in (0,1]$ of the population, the carrying capacity in the harvested or exploited area is defined by $(1-s)K$. Thus the growth functions of the population within and outside of the reserve are defined by

$$f(x_R, s) = rx_R(1 - \frac{x_R}{sK})^\alpha \tag{3}$$

$$f(x_{NR}, s) = rx_{NR}(1 - \frac{x_{NR}}{(1-s)K})^\alpha \tag{4}$$

where x_R is the population in the reserve.

To analyze the effects of reserves on rents and resilience, we incorporate stochastic shocks that may affect both the reserve and non-reserve population. We specify: one, a shock that may be either a positive or negative and represents *environmental stochasticity* due to temporal variation in the habitat (Shaffer 1981) and, two, a natural, and possibly harvesting induced, *negative shock* that occurs randomly over time. We define environmental stochasticity by 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 defined by the parameter λ.

The dynamic optimization problem with a reserve under uncertainty and with optimal harvesting of the exploited population is defined by

$$V(x_R, x_{NR}) = \max_{s,h} \int_0^\infty e^{-\rho t} \Pi(h, x_{NR}, s) dt \qquad (5)$$

subject to:

$$dx_R = [f(x_R, s) - \phi(1-s)(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K})]dt + g(x_R)dW + \psi(x_R)dq \qquad (6)$$

$$dx_{NR} = [f(x_{NR}, s) + \phi(1-s)(\frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K}) - h]dt + g(x_{NR})dW + \gamma(x_{NR})dq \qquad (7)$$

$$x_0 = x(0) \qquad (8)$$

where x_0 is defined as the sum of the initial population in the reserve and outside of the reserve and ρ is the discount rate. The transfer function is given by $\phi(\frac{x_R(1-s)}{sK} - \frac{x_{NR}}{K})$ and governs migration from the reserve to the exploited areas of the habitat. The absolute amount of fish transferred depends on the relative density of the populations in the reserve and the fishery, and allows for the possibility of transfers into the reserve if the population density is greater outside of the reserve. For a given difference in density between the reserve and fishery, the absolute amount of fish transferred is *decreasing* in reserve size to account for the fact that at a very large reserve size, very few fish are able to migrate into the fishery. The function $g(\cdot)$ represents the diffusion on the reserve and fishery populations from an increment of the Wiener process, dW. The functions ψ and γ differ to reflect the possibility that the proportional effects of negative shocks on the reserve and fishery populations may differ. For example, harvesting may

have a deleterious impact on the age structure and habitat such that, for a given negative shock, the consequences may be greater for the exploited than the reserve population. Using Ito's Lemma, Bellman's fundamental equation of optimality can be used to solve for the optimal reserve size and harvest trajectory, i.e.,

$$\rho V(x_R, x_{NR}) = \max_h \left\langle \begin{array}{l} \Pi(h, x_{NR}, s) + V_{x_{NR}}(x)[f(x_{NR}, s) + \phi(\frac{x_R(1-s)}{sK} - \frac{x_{NR}}{K}) - h] \\[2mm] + V_{x_R}(x)[f(x_R, s) - \phi(\frac{x_R(1-s)}{sK} - \frac{x_{NR}}{K})] + \\[2mm] \frac{1}{2}V_{x_R x_R}g(x_R)^2 + \frac{1}{2}V_{x_{NR} x_{NR}}g(x_{NR})^2 + V_{x_R x_{NR}}g(x_R)g(x_{NR}) + \\[2mm] \lambda[V(x_R + \psi(x_R), x_{NR} + \gamma(x_{NR})) - V(x)] \end{array} \right\rangle \quad (9)$$

Given the complexity of the stochastic jump-diffusion process, it is not possible to find a solution to (9) analytically. To solve for the optimal reserve size and harvest trajectory, we thus use a modified form of the perturbation method introduced by Gaspar and Judd (1997) and Judd (1999).[4] The method involves introducing two auxiliary variables (one for a Brownian diffusion process and another for the jump process) defined as η and ε to 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 $\Pi(h, x_{NR}, s, \eta, \varepsilon)$ and $V(x_{NR}, x_R, \eta, \varepsilon)$, and a nth 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. This process can be automated 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 is that which maximizes the value function.

4. OPTIMAL RESERVE SIZE

The desired size of a reserve will depend on many bioeconomic factors including the discount rate, intrinsic growth rate, carrying capacity, transfer function, current resource rent and the magnitude and incidence of shocks. Consequently, optimal reserve size will vary across populations and also over time as the underlying biological and economic parameters change. Our perturbation method, however, provides an approach to determine optimal reserve size for multiple populations and under a large number of different scenarios and conditions, provided that the value function is concave and the decision function is convex.

To illustrate the economic effects of reserves we specify demand and cost functions estimated from Canada's northern cod fishery (Grafton *et al.* 2000):

$$p(h) = ah^{-0.3} \qquad (10)$$

$$c(h, \frac{x_{NR}}{(1-s)K}) = \frac{bh(1-s)}{x_{NR}} \qquad (11)$$

where *a* and *b* are estimated to be, respectively, 0.35 and 0.2. Our initial biological parameters are also estimated from the northern cod fishery using 30 years of data and are $r = 0.30335$, $K = 3.2$ million and $\alpha = 0.35865$ while the initial population in the reserve and fishery is 1.8 million. We specify $\rho = 0.05$ and $\phi = 5$, where the latter parameter value corresponds to an instantaneous transfer of fish equivalent to around 10 percent of the steady-state population in the reserve following a negative shock.

The diffusion term is given by $g(x_R) = 0.01x_R$ and $g(x_{NR}) = 0.01x_{NR}$. The probability of the negative shock is 0.05 in both the reserve and fishery with jump amplitude of $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$ which implies a negative shock equal to a 10 percent reduction of the population in the fishery occurs, on average, every 20 years. Our assumption of a greater negative shock in the fishery is consistent with the fluctuations common in exploited fisheries (Hoffman and Powell 1998; Caddy and Gulland 1983), but even specifying identical shocks in the reserve and fishery we obtain qualitatively similar results. Using the above parameters, the simulations

were undertaken with the constraint that the transfer of fish from the reserve to the fishery cannot exceed the number of fish within the reserve and that the lowest obtainable value of *s* is positive, but within a neighborhood of zero.

Optimal reserve size

As a benchmark, we solve for the optimal reserve size under *no* uncertainty and find that, with an optimal harvest trajectory, a reserve generates no direct economic benefits. In other words, for the specified parameters, with no uncertainty, the value function is monotonically *decreasing* in the reserve size.

   In the case of uncertainty, with a diffusion process and also a jump process, we show that a reserve of size *s* > 0 is optimal under a large range of parameter values. In Figure 1 we show that even if the negative shocks are *identical*, that is $\psi(x_R) = -0.1x_R$ and $\gamma(x_{NR}) = -0.1x_{NR}$, we find that with both uncertainty and optimal harvesting outside of the reserve, a no-take area that protects a about 10 percent of the total population maximizes discounted rents. Thus even with optimal harvesting, risk neutrality, a persistent population and identical shocks in the reserve and fishery there is an economic payoff to having a reserve. This is an important result because it implies that a reserve and output controls are not equivalent if there is uncertainty, and that a reserve generates an extra economic payoff that cannot be obtained through harvest controls alone.

[Put Figure 1 here]

The case where there is a greater shock in the fishery than in the reserve, such that $\psi(x_R) = 0$ and $\gamma(x_{NR}) = -0.1x_{NR}$, is illustrated in Figure 2. By contrast to Figure 1, a greater negative shock outside of the reserve increases the economic payoff of a reserve and thus the optimal reserve size increases to around 40 percent of the total fishery. We emphasize, however, that in both cases that the economic payoff to a reserve holds true given any positive initial population size because the initial value only has transitory effects on the harvest rate. In other words, the value of the reserve is *not* obtained from initially being at a population level below that maximizes the economic rents from the fishery, and neither is it a result of risk-averse preferences.

[Put Figure 2 here]

The economic value of a reserve arises because it acts as a buffer and a population source for the exploited population, thus reducing the severity of negative shocks. Consequently, whenever a negative shock has at least an equal to or greater impact on the exploited than the reserve population, the reserve is able to help the fishery recover faster and increase harvest levels compared to the no-reserve case. This important result is illustrated in Figure 3 for the parameter values specified for Figure 2 in terms of the optimal harvest rate where the few, but large declines, in the harvest rate represent the jump process and the small and irregular fluctuations over much smaller time intervals are the effects of the diffusion process. As illustrated in Figure 3, the larger is reserve size the faster the harvest rate recovers to its optimal steady-state level following a negative shock.

[Put Figure 3 here]

Resilience and Volatility

The key result is that reserves mitigate negative shocks that are at least as great for the exploited population by raising the rate of harvest via the transfer of fish to the exploited area. This 'resilience effect' enables the population to recover faster and will tend to reduce the volatility of the population, harvest and rents. The resilience effect is shown in Figure 4 using the parameter values specified for Figure 2, where we define resilience as the mean period of time to return to within one standard deviation of the population level prior to the shock. In the figure, a shorter period of time represents a *higher* level of resilience, and resilience is increasing in reserve size.

[Put Figure 4 here]

We can also demonstrate that a reserve reduces the volatility of the resource rents, and that this stabilizing effect is accentuated in the case of rents the more elastic is the demand or the more sensitive harvesting costs are to changes in the exploited population. Our results are different from, but are consistent with the findings of Conrad (1999) who shows that uncorrelated net growth between the reserve and exploited area helps smooth biomass levels.

We emphasize that our resilience effect is *not* the same as increased population persistence. In our model, the population persists, in part, because the negative shocks are not sufficient to drive the population to zero and because it is sub-optimal to harvest until extinction. Thus irrespective of a reserve's ability to increase a population's persistence and raise its level above the minimum viable level (Lauck *et al.* 1998; Guénette *et al.* 1998), a reserve still has value because it enables the exploited population to rebound faster after a negative shock.

Biological Parameters

The resilience of a population to rebound following a shock is, in part, determined by its intrinsic growth rate. The higher the intrinsic growth rate, the quicker the population can rebound following a negative shock. Given that a reserve helps to increase the resilience of a population, we can show that, in general, the higher is the intrinsic growth rate the *smaller* is the optimal reserve size.

The transfer rate from the reserve to the exploited area also has an important impact on the value and size of reserves. Namely, the greater the number of individuals that leave the reserve and become subject to exploitation the less protection that is provided by a reserve of a given size. Thus the greater is the rate of transfer from the reserve to exploited areas the *larger* is the required reserve to provide a buffer in the event of a negative shock. These two results are summarized in Table 1.[5]

[Put Table 1 here]

Negative shocks

Another general result related to the resilience effect is that the larger are the negative shocks in the fishery, the larger will be the optimal reserve size. This result occurs because the greater is the magnitude of the shock, the greater is the share of the population required to be in a reserve so as to buffer the impact in the fishery and provide a source to the exploited population. A similar finding exists in terms of the probability of the negative shock in the fishery. Provided that the shock has at least an equal to or greater impact on the exploited than the reserve population, an increase in the probability of the shock will increase the optimal reserve size.[6]

Economic Variables

If the initial population is between zero and its maximum yield level then an outward shift in the inverse demand will immediately increase the harvest rate, but also *decrease* the sustained yield in the exploited population, thereby reducing its resilience. Consequently, at this lower population level a demand or price increase unambiguously increases the optimal reserve size to compensate for the loss of resilience. By contrast, if the population is between the maximum yield and its carrying capacity it is possible for the optimal reserve size to first decline and then to increase with an outward shift in the inverse demand because a marginal rise in the harvest rate at this population level will initially increase the sustained yield. However, whether or not a 'J-curve' relationship exists between the demand parameter and optimal reserve size, or whether the relationship is monotonically increasing, depends on the parameter values in the fishery and the reserve.

Another important result is that a rise in the discount rate will tend to reduce optimal reserve size. This comes from the fact that resilience generates a value to harvesters, but only to the extent that future harvests and returns are valuable. Our finding is illustrated in Figure 5 for the specified parameter values. The figure shows optimal reserve size is decreasing, but is also relatively insensitive to changes in the discount rate, such that even at a discount rate of more than 20 percent it is economically optimal to establish a marine reserve.

[Put Figure 5 here]

5. DISCUSSION

The results provide a number of important insights when establishing or enlarging reserves for harvested populations. We show a resilience effect where reserves have a positive economic value under uncertainty, even if harvesting is economically optimal. The beneficial effect of reserves in terms of increasing discounted rents arises whenever the magnitude of a negative shock for an exploited population is equal to or greater than the shock for the reserve population. In such circumstances, a reserve will *always* increase resilience thereby allowing the exploited population to rebound faster following a shock.

The resilience result is in direct contrast to existing deterministic models that suggest that effort controls and reserves are equivalent (Botsford *et al.* 2003, Hastings and Botsford 1999).

Moreover, the value of reserves in our model is separate from any benefits a reserve may generate to ensure population persistence (Lauck *et al.* 1998). Indeed, if it is optimal to have a reserve, the economic payoff of a reserve holds true for any positive initial population level. Our result contradicts the common presumption that reserves are only beneficial when population levels are low and current harvesting results in a decline in recruitment (Gerber *et al.* 2003, p. S58).

Our model generates a general result that the value function is concave given a positive optimal reserve size. This implies that if it is optimal to have a reserve, then any marginal increase in reserve size at less than the optimal size increases both resilience and the discounted rents from harvesting. This 'win-win' outcome has important policy implications, namely, even a small reserve less than its optimal size renders higher economic benefits to harvesters under uncertainty than no reserve. It suggests that for many harvested populations, and in the absence of data on key biological and economic parameters, an adaptive reserves policy where regulators initially establish small but less than optimal-sized reserves (that may be readjusted later with additional information) would be superior to having no reserves. Such a policy would also be consistent with the latest synthesis of the empirical effects of reserves where it has been found that a small reserve has the same proportional effect on biomass as a large reserve (Halpern 2003).

Overall, the results offer a number of new economic insights about marine reserves. First, with uncertainty, reserves can increase the economic payoff to harvesters even if harvesting is optimal, the population is persistent and fishers are risk neutral. Second, provided there exists a positive optimal reserve size even small, but less than optimal sized reserves, can generate a higher economic return than no reserve. Third, the economic benefits of reserves with uncertainty cannot be achieved by harvest controls alone. Fourth, as summarized in Table 1, optimal positive reserve size is increasing the smaller is the intrinsic growth rate (r), the larger the transfer rate from the reserve to exploited areas (ϕ), the larger the size ($\gamma(\cdot)$) and probability (λ in fishery) of negative shocks outside of the reserve, the smaller the size ($\psi(\cdot)$) and probability of the negative shock (λ in reserve) in the reserve, and the smaller the discount rate (ρ).

6. CONCLUDING REMARKS

Our paper answers the key question about marine reserves, namely, what is the optimal reserve size taking into account both the sustainability and rents from fisheries? Our findings are important

because over 150 nations at the World Summit on Sustainable Development (WSSD) pledged themselves to develop a worldwide network of marine reserves by 2012 and, until now, no model exists to determine optimal reserve size while incorporating environmental stochasticity and negative shocks.

Using a dynamic source-sink model, solved using a perturbation method, we show how to determine optimal reserve size for a harvested population subject to environmental uncertainty. Our results indicate that existing deterministic models understate the value of reserves and that even with optimal harvesting, risk neutrality and a persistent population a reserve can increase the present value of resource rents, provided that the effects of negative shocks on the reserve are at least as great for the exploited population. These findings are in stark contrast to the existing literature that has emphasized that if harvesting or effort can be controlled optimally, reserves are redundant.

The reason a reserve has economic value is because it increases an exploited population's resilience, or the speed at which it returns to a neighborhood of its initial level following a negative shock. Increased resilience allows for a greater harvest following a negative shock that, in turn, can raise the resource rents. Such a beneficial outcome can arise at any positive initial population size, and contradicts the presumption in the literature that reserves only have value for overexploited resources, or for populations particularly prone to extinction.

If a positive optimal reserve exists, which is the case under a wide range of parameter values, we show that with uncertainty the value function is concave with respect to reserve size. Thus even a small, but less than optimal, reserve size is economically beneficial to harvesters while also rendering possible ecological benefits. The implication is that marine reserves do not need to be large to render economic benefits. Moreover, initially establishing small reserves and adjusting to a larger and optimal size later after collecting relevant bioeconomic data, is likely to be a desirable strategy in many harvested populations subject to negative shocks.

Overall, we provide an important economic justification for marine reserves, a method for determining optimal reserve size and bioeconomic 'rules of thumb' regarding optimal reserve size. Such insights are needed as countries move forward in their international commitments to establish marine reserves and address the problems of managing renewable resources with uncertainty.

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Table 1: Effect of Marginal Increase in Parameter Values on Optimal Reserve size

	r	ρ	ϕ	ψ	λ (reserve)	γ	λ (fishery)
Optimal Reserve Size	-	-	+	-	-	+	+

N.B: A (+) indicates that an increase in the given parameter value, holding all other parameters unchanged, will *increase* a positive optimal reserve size while (-) indicates it will *reduce* reserve size.

End Notes

[1] The WSSD plan of implementation (article 32(c)) requires "…the establishment of marine protected areas consistent with international law and based on scientific information, including representative networks by 2012…"

[2] The National Research Council (2001, pp. 111-118) discusses the proposals for a minimum 20 percent reserve in the coastal waters of the United States. Using a bioeconomic model of the North Sea ecosystem Beattie *et al.* (2002) recommend a reserve size of between 25-40 percent of its surface area.

[3] Pimm (1984, p. 325) defines resilience as the *speed* at which a species composition returns to an equilibrium following a shock. Holling (1973, p. 20) measures it in two ways: one, the extent to which a domain of attraction of the trajectories for a group of species does not include points of extinction and two, the *magnitude* of a shock required to place a group of species into a trajectory that leads to extinction. Our notion of resilience refers to a single species and the speed with which it rebounds from a shock to return to within a neigborhood of its value immediately before the shock.

[4] The case for solving more realistic, but complicated models, by numerical methods in place of more simple models where analytic solutions and theorem proving are available, is made forcefully by Judd (1997). A general topological proof for the existence of an optimal solution (and a concave value function) in a system similar to (9), but without the jump process, is given in Atakan (2003).

[5] The results that show a negative relationship between optimal reserve size and the intrinsic growth rate, and a positive relationship between optimal reserve size and the transfer rate, are available from the authors upon request.

[6] The results that show the negative relationship between the size and the probability of the negative shock on optimal reserve size are available from the authors.
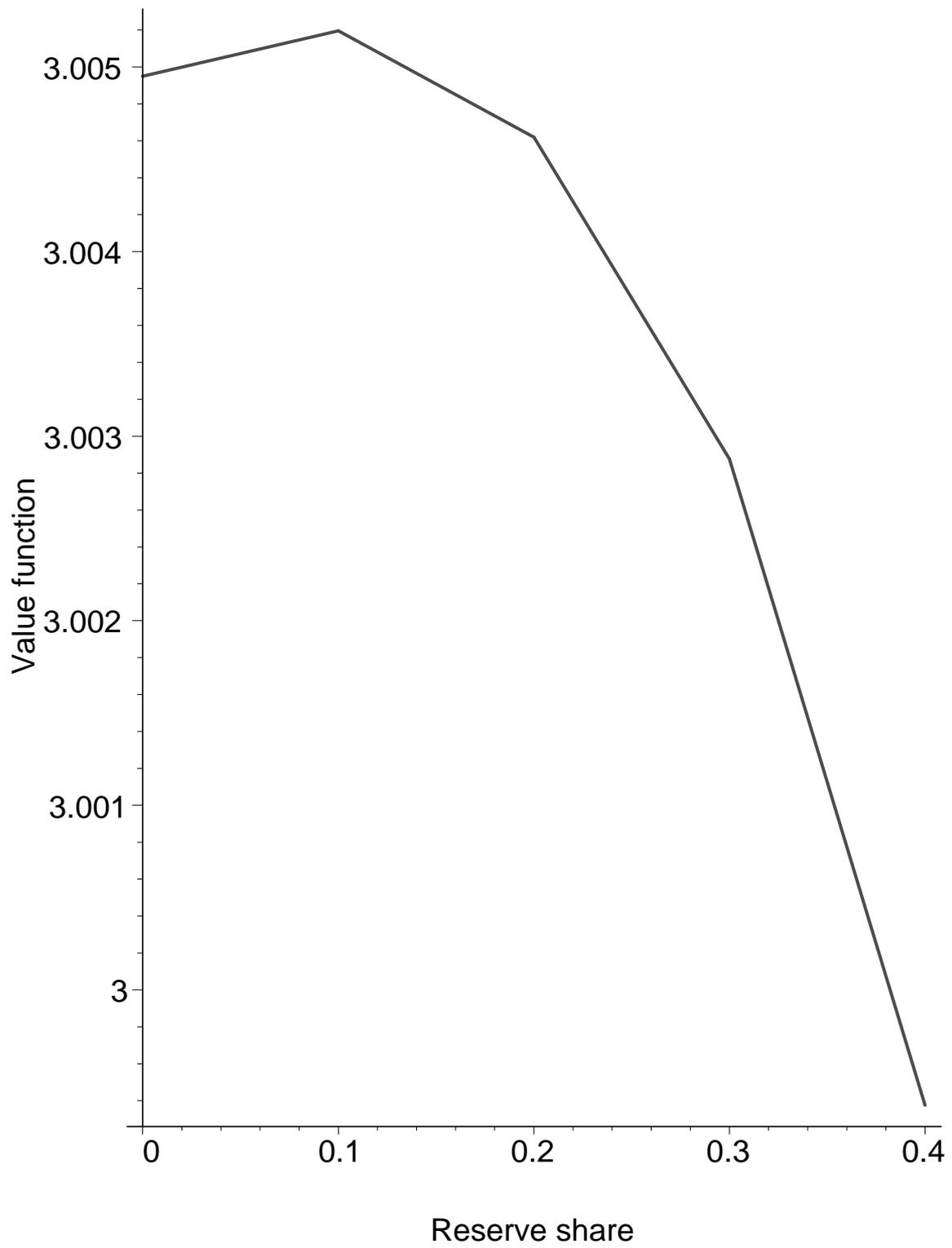
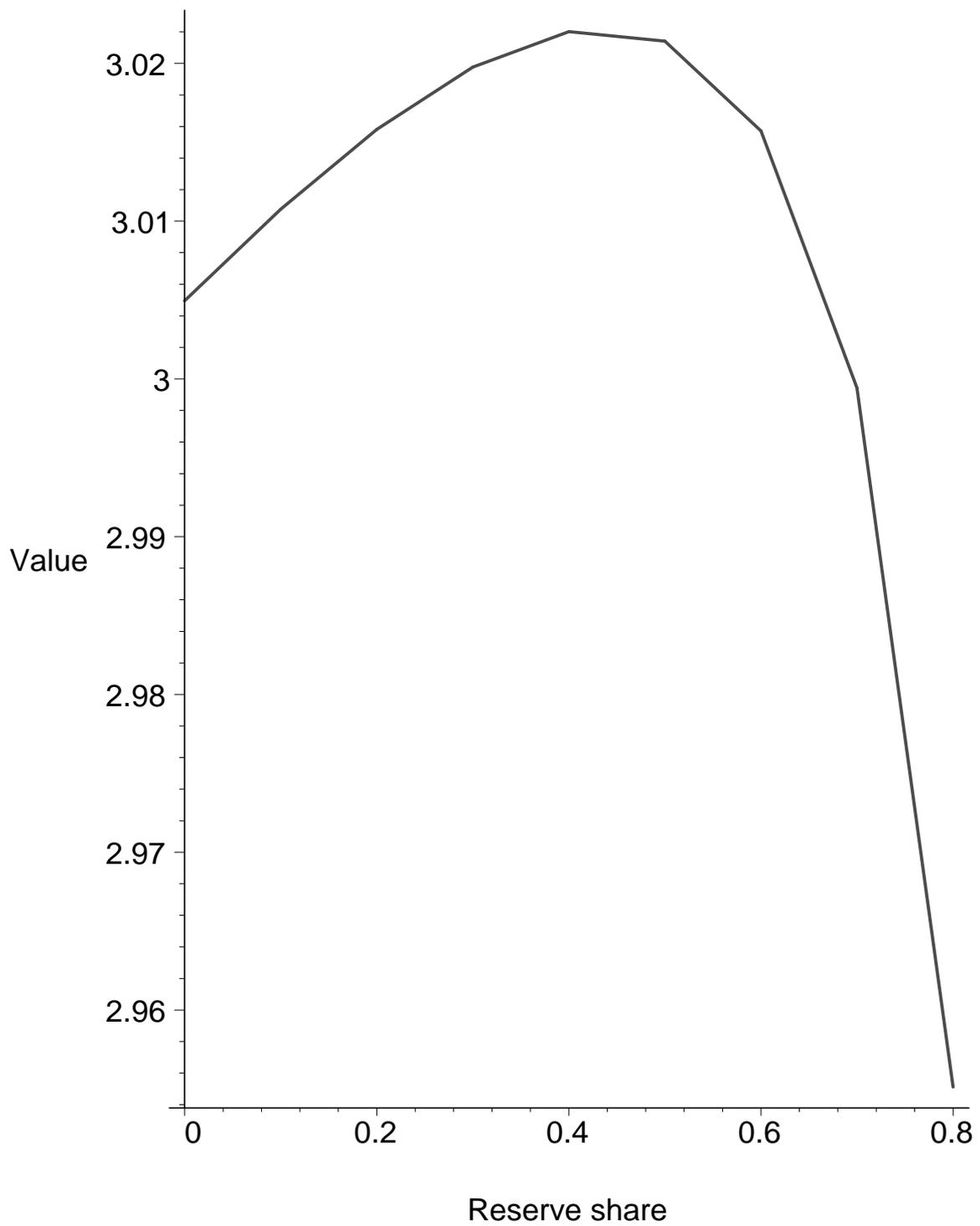Figure 1: The value function and reserve size $(\psi(x_R) = -0.1x_R, \gamma(x_{NR}) = -0.1x_{NR}, \lambda = 0.05)$

Figure 2: The value function and reserve size $(\psi(x_R) = 0, \gamma(x_{NR}) = -0.1x_{NR}, \lambda = 0.05)$
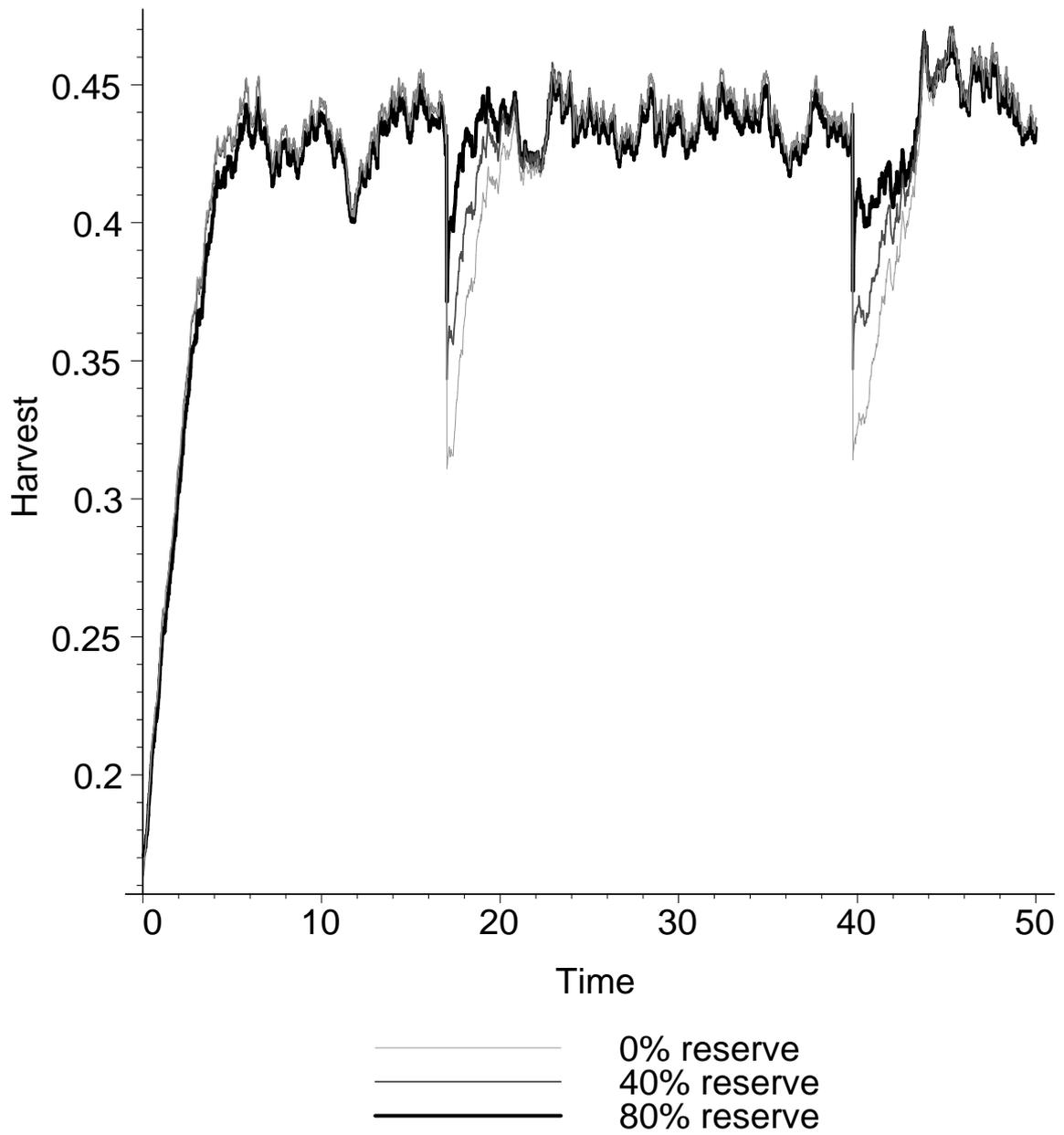
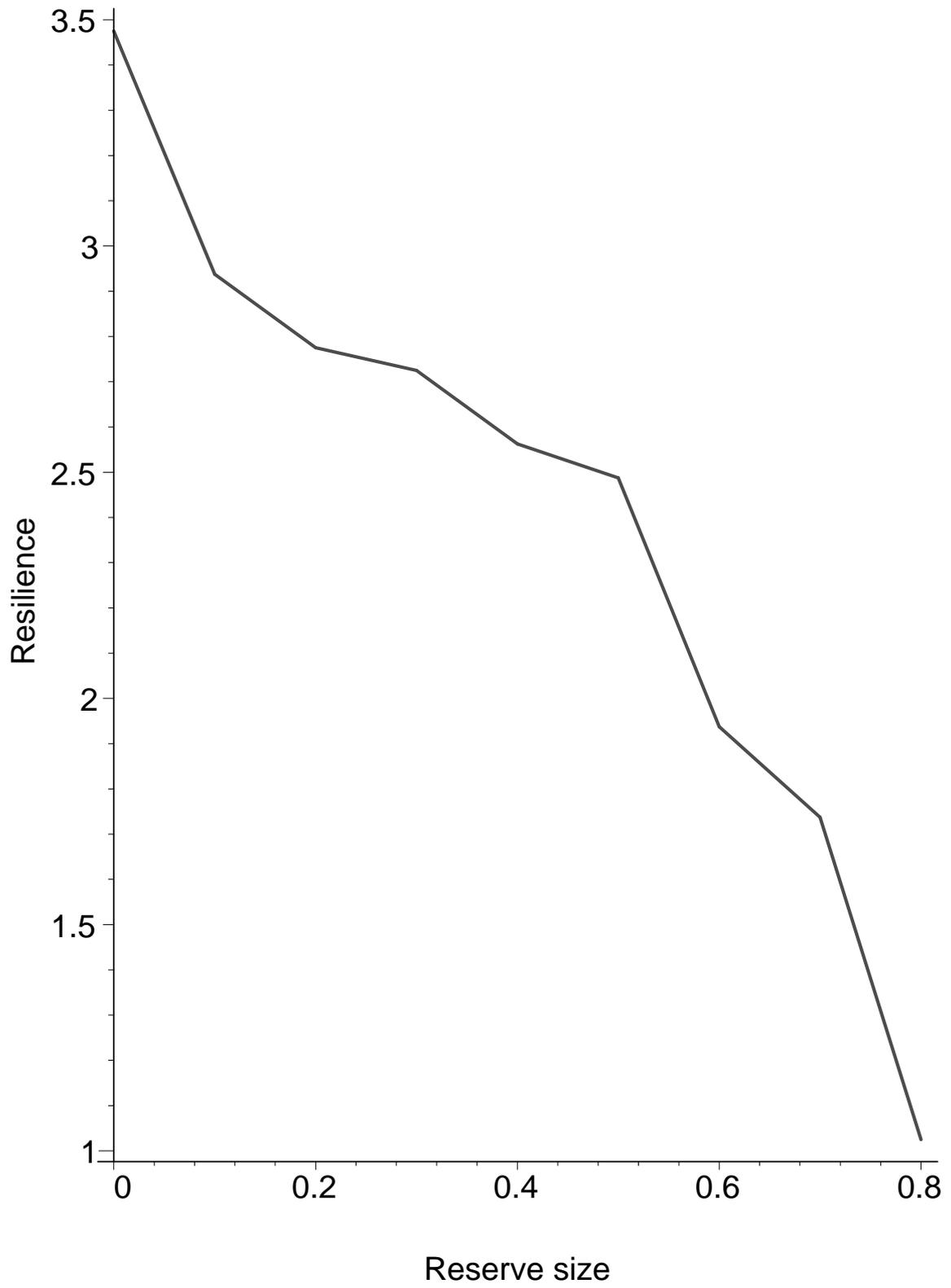Figure 3: Relationship between harvest rate and reserve size

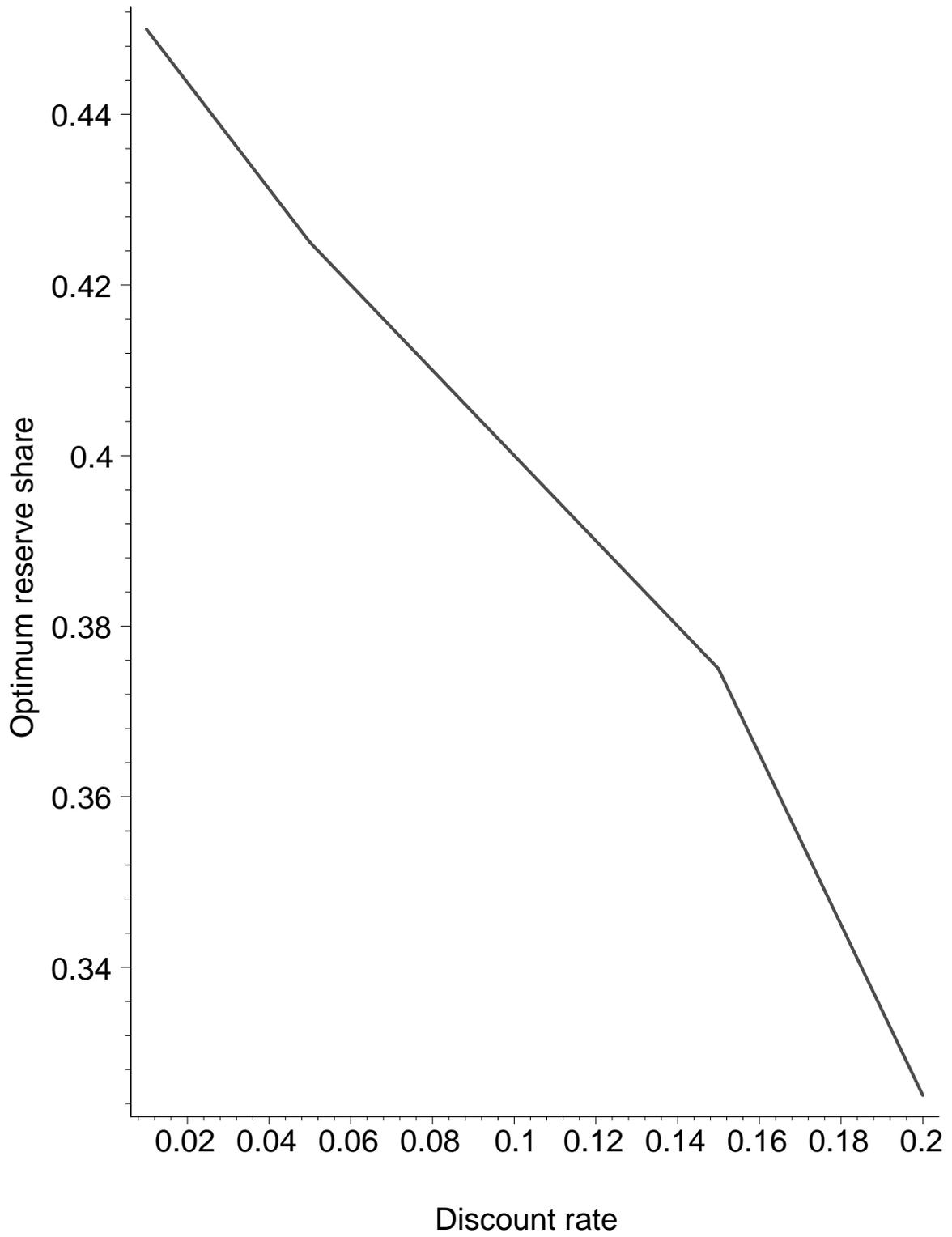Figure 4: Relationship between resilience of the biomass in the fishery and reserve size

Figure 5: Relationship between discount rate and optimal reserve size