

# The Economic Payoffs from Marine Reserves: Resource Rents in a Stochastic Environment\*

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*In this paper we analysed the economic payoffs from marine reserves using a stochastic optimal control model, with a jump-diffusion process. The results show that even if the reserve and harvested populations face the same negative shocks, harvesting is optimal, the population is persistent and there is no uncertainty over current stock size, a reserve can increase resource rents. Using fishery data we demonstrate that the payoffs from a reserve, and also optimum reserve size, increase the larger is the magnitude of the negative shock, the greater its frequency and the larger its relative impact on the harvested population.*

## *I Introduction*

A decade ago there were over 1300 marine reserves worldwide, and many more reserves are

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planned (Botsford *et al.*, 1997).<sup>1</sup> Under some proposals, marine protected areas could increase from less than 1 per cent of the earth's oceans (Boersma & Parrish, 1999), to 20 per cent or more of marine coastal areas (Agardy *et al.*, 2003).<sup>2</sup> If this commitment is achieved, it will represent the largest ever transformation in the use (or rather non-use) of the earth's surface.

<sup>1</sup> The World Summit on Sustainable Development plan of implementation (article 32(c)) also requires '... the establishment of marine protected areas consistent with international law and based on scientific information, including representative networks by 2012 ...' (United Nations, 2002).

<sup>2</sup> The National Research Council (2001: 111–118) discusses the proposals for a minimum 20 per cent reserve in the coastal waters of the USA. Using a bio-economic model of the North Sea ecosystem, Beattie *et al.* (2002) recommend a reserve size of between 25 and 40 per cent of its surface area.

Despite the increasing adoption of marine reserves as a fisheries management tool, and the commitment in some countries, such as Australia, to establish a National Representative System of Marine Protected Areas, the economic benefits of reserves for fishers remain uncertain. Indeed, many fishers oppose the establishment of reserves (National Research Council, 2001) and claim that 'no take' areas would be redundant if existing management tools (gear restrictions, effort and output controls, etc.) were properly implemented. In this paper we investigated the economic payoffs of reserves to fishers in a stochastic environment that includes two forms of uncertainty (a continuous diffusion process and a jump process), and with harvesting that maximises the discounted net returns from fishing, taking into account both the size and probability of the stochastic processes.

Our approach allows us to analyse the benefits of reserves to fishers with environmental uncertainty, *separate* from any payoffs that may arise from management uncertainty over stock size or fishing effort, suboptimal harvesting, or whether the population is subject to extinction. Our results indicate that spillovers, or transfers of fish from the reserve to harvested population, allow for a larger harvest and can increase resource rents following a shock that lowers the overall population, even if harvesting is optimal. These spillovers also create a resilience effect that allows the harvested population to recover faster from a negative shock.<sup>3</sup> We show that the economic payoff from a reserve and its optimum size are increasing the larger the size of the negative shock is, the more frequent its occurrence, and the larger its proportional impact on the harvested relative to the reserve population.

In the following section, we briefly review the literature on marine reserves. We then outline in Section III the bio-economic model and perturbation method we use to determine the economic payoffs associated with a reserve. In Section IV we simulate the economic effects of a marine reserve using parameters estimated from an actual fishery under a range of scenarios, and also analyse the effects of biological and economic variables on the payoffs from a reserve. Concluding remarks are offered in Section V.

<sup>3</sup> We used Pimm's (1984: 325) notion of resilience. He defined it as the *speed* at which a species composition returns to an equilibrium following a shock.

## *II The Bio-economics of Marine Reserves*

A huge literature exists in terms of marine reserves, mostly written from a biological perspective.<sup>4</sup> A key insight is that how many, and under what conditions, fish migrate or spill over from reserves to harvested areas is critical to maximising the direct benefits of 'no take' areas (Polachek, 1990). These spillovers occur whenever individual fish are afforded a measure of protection in a reserve, but also provide a source of recruitment for exploited areas outside of the reserve (Pulliam, 1988).

Roberts *et al.* (2001) and McClanahan and Mangi (2000), among others, provide empirical evidence that reserves can generate positive spillovers that may improve harvests in adjacent exploited areas. Pezzey *et al.* (2000) and Sanchirico and Wilen (2001) have shown 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 population. However, this 'double payoff' only arises when the chosen area for the reserve is at a low population level such that the marginal benefits of a closure – reduced mortality, but with spillovers – outweigh the loss of harvest in a previously exploited area.

### *(i) Deterministic Bio-economic Models*

One of the earliest economic contributions to the reserve literature is by Holland and Brazee (1996), who used a deterministic model to show that the relative benefits of reserves depend on their effects on harvesting in exploited areas and also the discount rate. They found that with very high levels of fishing effort a reserve provides insurance against a collapse in the population, but emphasise that reserves give little or no benefit if there exist effective controls on effort or catches. Hannesson (1998) obtained a similar result, showing that a reserve would need to be of a very large size (with excessive fishing effort) to generate harvesting benefits that are equivalent to an optimally controlled fishery. In contrast, Neubert (2003) used a spatially explicit model to show that reserves can increase yields, but this result critically depends on boundary conditions that assume fish live in patches of suitable habitat, beyond which they die.

<sup>4</sup> Reviews of the literature include Guénette *et al.* (1998), the National Research Council (2001), Ward *et al.* (2001) and Gell and Roberts (2002). A recent and selected review of the biological and economics literature of marine reserves is Grafton *et al.* (2005a).

Holland (2000) observed in a spatially explicit model that optimal controls on effort and catches make reserves superfluous, but stresses there can be a positive economic payoff to a reserve if fishing effort is excessive. Sanchirico (2004) also found in a spatial model that a first-best strategy is to optimally set fishing effort in every possible fishing location, but that establishing reserves in some patches can generate a higher resource rent in an open access fishery. He emphasised, as did Sanchirico and Wilen (1999), that the costs and returns of harvesting in different locations, as well as the spillovers, play an important role in determining where to establish reserves.

### (ii) Stochastic Models

Lauck *et al.* (1998) showed that if there exists management uncertainty over population size, marine reserves should increase with the size of the negative shocks to ensure population persistence. Mangel (1998, 2000a) generates a similar result whereby reserve size should increase with the size of an uncertain harvest rate so as to ensure sustainability of the population. Li (2000) found that if the probability of total stock collapse decreases with the size of a marine reserve, a reserve has an economic value. Sumaila (1998) also showed that reserves mitigate against biological losses that may arise due to recruitment failure. Grafton *et al.* (2005b) found that reserves increase resilience in the presence of negative shocks, but did not use parameters from an actual fishery and failed to examine the harvesting trade-offs of establishing a reserve, the effects of fish transfers on these trade-offs and the sensitivity of economic parameters and the probability of negative shock on optimum reserve size. In a bio-economic model, Conrad (1999) showed that reserves may generate economic benefits by reducing the variance of the population if net growth in the reserve and the fishery are uncorrelated, or if they are perfectly correlated. In addition, Sladek Nowlis and Roberts (1998), Mangel (2000b) and Hannesson (2002) demonstrated that with environmental variability a reserve can lower the harvesting variance.

Those who incorporate stochasticity into their models show that reserves have value because either they mitigate the effects of environmental surprises and help ensure population persistence given management error (inability to control harvests) or management uncertainty (imprecise information on current population), or because they reduce the variance of populations and harvests. Many fishers and some fishery managers

have used these findings to conclude that if harvesting is 'optimal', and the population is persistent, marine reserves generate no harvesting payoffs to fishers and are a redundant management tool. Using a stochastic bio-economic model, we examine whether fishers can, in fact, benefit from a marine reserve under conditions where 'no take' areas are, at best, viewed as superfluous or even harmful to fisher incomes.

### III A Stochastic Bio-economic of a Marine Reserve

To address the question of what is the economic payoff of a reserve to fishers, we explicitly model environmental uncertainty. We assume that the population, without harvesting and uncertainty, is governed by density-dependent growth defined by

$$f(x) = rx \left(1 - \frac{x}{K}\right) \quad (1)$$

where  $x$  is the population or biomass,  $f(x)$  is its growth,  $r$  is the intrinsic growth rate, and  $K$  is the carrying capacity.

Following Grafton *et al.* (2005b), the model assumes the economic benefit from the population is simply the resource rents it generates, and thus ignores the value of reserves in terms of biodiversity (Hastings & Botsford, 2003). This assumption allows us to determine if a reserve is worthwhile only in terms of the economic payoffs it provides to fishers, separate from any benefits associated with population persistence, management error, management uncertainty over stock size, or the existence of ecological (Roberts *et al.*, 2003) and non-market (Bhat, 2003) values.

Intertemporal rents from harvesting the population are defined by

$$\Pi(h, x_{NR}) = p(h)h - c\left(h, \frac{x_{NR}}{K_{NR}}\right) \quad (2)$$

where  $h$  is harvest,  $x_{NR}$  is the size of the harvested population,  $K_{NR}$  is the carrying capacity of the harvested population,  $p(h)$  is the inverse demand

function, and  $c\left(h, \frac{x_{NR}}{K_{NR}}\right)$  is the aggregate cost function where costs rise with the harvest, but do not increase with population density of the harvested population.

In the case of a permanent reserve that protects proportion  $s \in (0, 1]$  of the population, the carrying capacity of the harvested population is defined by  $(1 - s)K$ . Thus, for  $s > 0$  the growth function of the reserve population,  $f(x_R, s)$ , and the harvested population,  $f(x_{NR}, s)$ , are

$$f(x_R, s) = rx_R \left(1 - \frac{x_R}{sK}\right) \quad (3)$$

$$f(x_{NR}, s) = rx_{NR} \left(1 - \frac{x_{NR}}{(1-s)K}\right) \quad (4)$$

where  $x_R$  and  $x_{NR}$  are the reserve and harvested populations.<sup>5</sup> In our model we assume  $r$  and  $K$  are the same for both the reserve and harvested populations, but in practice they may differ – especially in the case of a long-established reserve.<sup>6</sup>

To analyse the effects of reserves on resource rents, we incorporate two stochastic shocks that may affect both the reserve and harvested populations. One shock may be either positive or negative and represents a temporal variation in both populations, as defined by a Wiener diffusion process (Brownian motion) that follows a normal distribution ( $W$ ). The other stochastic process is a negative shock that occurs randomly over time and is defined as a jump process ( $q$ ) that follows a Poisson distribution, governed by the parameter  $\lambda$ .

Brownian motion in the reserve and harvested population is defined by  $g(x_R)$  and  $g(x_{NR})$  that represent the proportional effect on the two populations from the same realisation,  $dW$ . Sensitivity to negative shocks in the reserve and harvested population is defined by  $\psi(x_R)$  and  $\gamma(x_{NR})$  that represent the proportional effects on the populations from the same realisation,  $dq$ . The functions  $\psi$  and  $\gamma$  differ to allow for the possibility that the sensitivity to the negative shocks may vary in the reserve and harvested populations.

To solve for the optimal harvest trajectory and reserve size, we must first determine the optimal harvest for a given reserve size, and then select the reserve size that maximises the overall value function defined over  $s \in (0,1]$ . Thus, the solution to the overall optimisation problem is defined over all possible values of  $s$  and involves the selection of both a harvesting trajectory and a reserve size

<sup>5</sup> We note that  $x_R = \frac{sK}{1 + (K/x_0 - 1)e^{-\rho t}}$  such that as  $s \rightarrow 0$  then  $x_R \rightarrow 0$ .

<sup>6</sup> Assuming a higher value of  $r$  and  $K$  in the reserve compared to the harvested population increases the economic payoffs from a reserve in our simulations. Thus, our specification of a common  $r$  and  $K$  in the reserve and non-reserve areas *understates* the resource rent associated with reserves if fishing causes habitat destruction or undesirable changes to the age structure that negatively affect either the intrinsic growth rate of the harvested population or the carrying capacity of the harvested population, defined by  $(1-s)K$ .

that maximise the discounted net returns from fishing.

The initial harvest optimisation problem, incorporating the two stochastic processes and for an arbitrary  $s$ , is defined by Equations 5 to 8,

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

subject to

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

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

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

where  $V(x_R, x_{NR})$  is the value function,  $x_0$  is the sum of the initial population in and outside of the reserve,  $\rho$  is the discount rate and  $\phi$  is the transfer coefficient.

The transfer function,  $\phi(1-s)K \left( \frac{x_R}{sK} - \frac{x_{NR}}{(1-s)K} \right)$ , is

compatible with diffusion models in fisheries that suggest reserve size directly influences dispersal (Kramer & Chapman, 1999),<sup>7</sup> and is also consistent with evidence that dispersion is strongly density dependent (MacCall, 1990).<sup>8</sup> Our specification ensures the transfer of fish is governed by both reserve size and the relative population density of the reserve and harvested populations, but also allows for the possibility of transfers into the reserve if the population density is greater outside of the reserve.

<sup>7</sup> The term  $(1-s)$  that multiplies the density difference in the two populations ensures that for a given difference, the absolute amount of fish transferred is decreasing in reserve size. This accounts for the fact that if a reserve were established that protected a very high percentage of the population, very few fish would be able to migrate to locations where they would actually be vulnerable to exploitation. Our results about the economic payoffs from reserves, however, are robust to alternative specifications of the transfer function.

<sup>8</sup> We note that recent work on marine reserve design suggests that a diffusion mode of transfer is likely to understate the potential spillovers if marine reserves were designed to account for advection and flow-generated connectivity across sites (Gaines *et al.*, 2003: S45).

Using Ito's Lemma, Bellman's fundamental equation of optimality can be used to solve for the harvest trajectory for any given reserve size, that is,

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

Given the complexity of the stochastic jump-diffusion process, it is not possible to find a solution to (9) analytically, but it can be solved numerically with a modified form of the perturbation method introduced by Gaspar and Judd (1997) and Judd (1997).<sup>9</sup> The method involves introducing two auxiliary variables (one for a Brownian diffusion process and another for the jump process) defined as  $\eta$  and  $\varepsilon$  to the Bellman equation, where if  $\eta = \varepsilon = 0$  the deterministic problem results. Following the substitution, for a given  $s$ , the harvest function and value function can be defined as  $h(x_R, x_{NR}, \eta, \varepsilon)$  and  $V(x_R, x_{NR}, \eta, \varepsilon)$ , and an  $n$ th order Taylor series expansion can be defined around the steady state in the deterministic case.

<sup>9</sup> 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, 1999). A general topological proof for the existence of an optimal solution (with a concave value function) in a system similar to (9), but without the jump process, is given in Atakan (2003).

In the first step to solving (9), we find 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  $V_\eta$  and  $V_\varepsilon$  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 using Taylor series approximations.

We automated the solution process for all possible values of  $s$  by using MAPLE to calculate the partial derivatives of the optimal value function and control variables with respect to the state and auxiliary variables. This allows us to solve for the optimal harvest levels for any given reserve size. The optimal reserve size ( $s^*$ ) is that which gives the highest economic value for all possible reserve sizes and maximises the overall value function,  $V^*(x_R, x_{NR})$ , that is an envelope of value functions for all possible values of  $s$ .

#### IV The Economic Payoffs from Marine Reserves

The economic payoffs to fishers from a reserve will depend on many bio-economic factors including the discount rate, intrinsic growth rate, carrying capacity, transfer function and the magnitude and incidence of shocks. Our perturbation method, however, provides an approach to assess the economic benefits from reserves by varying any, or all, of these parameters.

To illustrate the economic effects of reserves, we use the following inverse demand and cost functions,

$$\ln p = a + b \ln h \quad (10)$$

$$c \left( h, \frac{x_{NR}}{(1-s)K} \right) = \frac{ch(1-s)}{x_{NR}} \quad (11)$$

Equation 10 is estimated from annual data (Quinn *et al.*, 1985; International Pacific Halibut Commission, 1986), using real prices, over the period 1929–1986 from the Pacific halibut fishery, which has one of the world's longest continuous records of stock size and harvests. The inverse demand parameters,  $a$  and  $b$ , are estimated (standard errors in parentheses) to be  $-2.6599$

(0.4160) and  $-0.81$  (0.1364).<sup>10</sup> Equation 11 is of a form used in other fisheries (Grafton *et al.*, 2000), but in the absence of adequate cost data cannot be estimated for the Pacific halibut fishery. Instead, we specify  $c = 0.17$ , and undertake sensitivity analysis to assess its effect on reserve size and the economic payoffs from a reserve.<sup>11</sup>

Our biological parameters are also estimated from annual data for the Pacific halibut fishery over the period 1935–1983. The estimates (standard errors in parentheses) are  $r = 0.2985$  (0.0297) and  $K = 0.9631$  million pounds (0.0238).<sup>12</sup> We also test for the presence of negative shocks using annual dummies over the 49-year period and find that the only significant negative shocks in the population occurred in 1964 and 1965 when it declined by some 13 per cent in both years.<sup>13</sup> In our simulations, we initially specify  $\rho = 0.05$  and  $\phi = 1.0$ , but undertake sensitivity analysis to determine their effects on reserve size and the economic payoffs from a reserve.

#### (i) Resource Rents and the Probability and Size of Negative Shocks

Identical positive and negative stochastic effects in the reserve and harvested population are

<sup>10</sup> The series for  $\ln p$  and  $\ln h$  are both non-stationary and  $I(1)$ . However, residuals are  $I(0)$  with a test statistic of  $-3.546$  (compared to a critical value of  $-2.606$  at the 1 per cent level of significance), indicating that the two series are co-integrated and that basic ordinary least-squares regression estimates of Equation 10 are ‘superconsistent’. All estimates and the dataset are available from the authors on request. Because of data limitations, it was not possible to estimate a simultaneous supply and demand system instead of Equation 10. Although there is a potential for bias because of this and any other omitted variables, it is important to note that variations in the parameters  $a$  and  $b$  do not qualitatively change the results for the presence of an optimal reserve. Sensitivity on  $a$ , for example, over the range of  $-3.47$  to  $-2.29$  generates an optimal reserve that varies from 40 to 20 per cent of the fishery. Changes in  $b$  affect reserve size to a much lesser extent. All sensitivity results are also available from the authors on request.

<sup>11</sup> We vary  $c$  from 0.1 to 0.5 and in a base-case result (a negative shock in the harvested area of  $-13$  per cent that arrives about every 25 years) generate positive economic payoffs from a marine reserve for all values. We also find that optimal reserve size is increasing in the parameter  $c$  over this interval.

<sup>12</sup> Our estimates are very similar to those obtained by Hilborn and Walters (1992: 317) who use a different data coverage and estimate  $r = 0.31$  and  $K = 1.0006$  million pounds.

<sup>13</sup> The estimated parameters (standard errors in brackets) for the dummies in 1964 and 1965 are  $-0.1362$  (0.0381) and  $-0.1247$  (0.0428), respectively.

specified by  $g(x_R)dW = 0.05x_RdW$  and  $g(x_{NR})dW = 0.05x_{NR}dW$ . These impacts affect the variance of the population, harvest and resource rents, but play no direct role in our comparison of the economic payoffs from a marine reserve. However, if the stochastic process were to include negative drift, it would alter the economic benefits associated with a reserve.

The negative shocks are defined by the arrival rate, or probability of occurrence, and the size of the sensitivity of the shock in the reserve,  $\psi(x_R)$ , and harvested population,  $\gamma(x_{NR})$ . We analysed the outcomes with equal shock sensitivities, that is,  $\psi(x_R) = -0.13x_R$  and  $\gamma(x_{NR}) = -0.13x_{NR}$ , but also allow for the case of differential shock sensitivities, that is,  $\psi(x_R) = 0$  and  $\gamma(x_{NR}) = -0.13x_{NR}$ . The case for different shocks comes from empirical evidence that finds some fishing methods damage habitat (Goñi, 1998; Turner *et al.*, 1999; Jennings *et al.*, 2001), and that fishing can have a deleterious impact on the age structure (Trippel, 1995; Palumbi, 2004) that can make the harvested population more vulnerable to environmental disturbances.

Table 1 illustrates the economic payoffs of a reserve with optimal harvesting assuming a 13 per cent negative shock in the harvested population and for different arrival rates, measured in years. The table shows that only if the negative shock occurs every 200 years does it *not* pay to have a marine reserve. For an arrival rate, or an incidence of a negative shock, more frequent than this, a reserve generates an economic payoff to fishers by increasing resource rents. This shows that a reserve and output controls are not equivalent if a harvested population is subject to stochastic shocks. In other words, a reserve generates an extra economic payoff that cannot be obtained through harvest controls alone, even if they are applied optimally, as is the case in our model.

Table 1 also illustrates that the more frequent the occurrence of the negative shocks, the larger will be the optimal reserve size. A similar result is also found in terms of the magnitude or sensitivity of the negative shock on the harvested population. Table 2 shows the economic payoff from a reserve with negative shocks varying from 5 to 30 per cent with an arrival rate of every 25 years. Provided the shock is 5 per cent or greater in the fishery, and given an arrival rate of every 25 years, a reserve generates an economic payoff to fishers. In comparison, shocks in many fisheries are much more substantial and occur more frequently than we suppose in our base case (Caddy & Gulland, 1983; Hofmann & Powell, 1998).

TABLE 1  
*Values for Different Arrival Rates and Reserve Shares*

Arrival rate	Reserve shares (percentage of total population)									
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
200	<b>0.59270</b>	0.59269	0.59257	0.59230	0.59181	0.59101	0.58966	0.58728	0.58255	0.56984
40	0.59139	0.59152	<b>0.59153</b>	0.59138	0.59101	0.59032	0.58907	0.58680	0.58217	0.56955
20	0.58974	0.59004	0.59022	<b>0.59023</b>	0.59001	0.58946	0.58834	0.58620	0.58168	0.56920
15	0.58861	0.58904	0.58933	<b>0.58945</b>	0.58933	0.58887	0.58785	0.58579	0.58136	0.56896
10	0.58640	0.58707	0.58759	0.58792	<b>0.58800</b>	0.58773	0.58688	0.58499	0.58072	0.56849

*Notes:*

1. Cells marked in bold correspond to reserve size that maximises the value function for a given arrival rate.
2. Shock magnitude or sensitivity is  $-13$  per cent for the harvested population and 0 per cent for the reserve population.

TABLE 2  
*Values for Different Negative Shocks Sensitivities in the Harvested Population and a Zero Negative Shock Sensitivity in the Reserve*

Shock sensitivity in harvested population	Reserve share (percentage of total population)									
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$-5\%$	0.59184	<b>0.59191</b>	0.59187	0.59168	0.59127	0.59054	0.58926	0.58695	0.58229	0.56964
$-10\%$	0.59055	0.59077	<b>0.59086</b>	0.59079	0.59050	0.58987	0.58869	0.58648	0.58191	0.56937
$-15\%$	0.58917	0.58954	0.58978	<b>0.58985</b>	0.58968	0.58917	0.58811	0.58600	0.58153	0.56908
$-20\%$	0.58767	0.58823	0.58864	<b>0.58886</b>	0.58883	0.58845	0.58750	0.58550	0.58114	0.56880
$-30\%$	0.58604	0.58681	0.58741	0.58781	<b>0.58794</b>	0.58770	0.58687	0.58499	0.58073	0.56850

*Notes:*

1. Cells marked in bold correspond to a reserve size that maximises the value function for a given shock sensitivity in the harvested population.
2. Arrival rate of the negative shock is every 25 years.

TABLE 3  
*Values with Identical Negative Shock Sensitivities in Reserve and Harvested Populations*

Shock sensitivity in reserve and harvested population	Reserve share (percentage of total population)									
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$-5\%$	<b>0.59226</b>	0.59222	0.59207	0.59178	0.59127	0.59044	0.58907	0.58668	0.58195	0.56925
$-10\%$	<b>0.59098</b>	0.59097	0.59084	0.59055	0.59005	0.58923	0.58786	0.58548	0.58075	0.56809
$-15\%$	0.58961	<b>0.58963</b>	0.58953	0.58927	0.58878	0.58796	0.58660	0.58422	0.57949	0.56686
$-20\%$	0.58812	<b>0.58821</b>	0.58815	0.58792	0.58745	0.58664	0.58528	0.58289	0.57816	0.56555
$-25\%$	0.58652	0.58669	<b>0.58670</b>	0.58651	0.58606	0.58526	0.58389	0.58149	0.57675	0.56415
$-30\%$	0.58479	0.58507	<b>0.58516</b>	0.58502	0.58461	0.58382	0.58244	0.58002	0.57526	0.56267

*Notes:*

1. Cells marked in bold correspond to a reserve size that maximises the value function for a given negative shock sensitivity.
2. Arrival rate of the negative shock is every 25 years.

Table 2 illustrates that the larger the shock sensitivity, the greater the optimal reserve size and the greater payoff from a reserve of optimal reserve compared to no reserve. This result holds true even if the reserve and the fishery face the same

shock sensitivities, as shown in Table 3. In other words our results do *not* depend on the assumption of a smaller negative shock in the reserve than in the harvested population. In the case of equal negative shocks to both the reserve and harvested populations,

a marine reserve can still generate higher resource rents, but only when the magnitude of the shock is about 15 per cent or greater, given an arrival rate of every 25 years. We can also show the benefits of a reserve in the case of *positive* shocks provided that the proportional impact on the reserve is equal to or greater than on the harvested population. However, in the absence of any negative shocks, or if the negative shocks are substantially greater in the reserve than in the harvested population, a reserve will not generate a positive economic payoff with optimal harvesting.

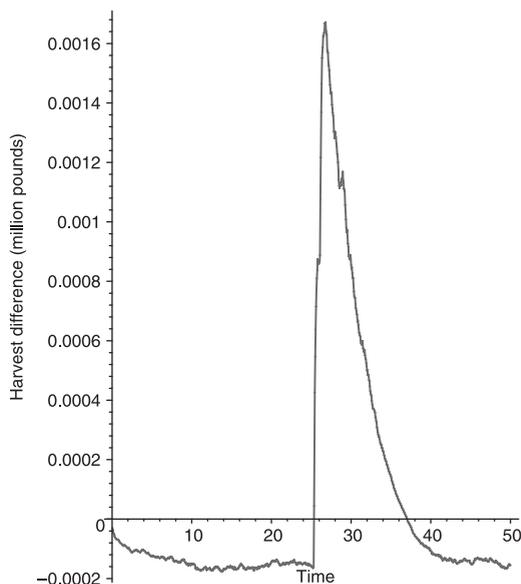
The actual figures from the simulations presented in Tables 1–3 are not as important as what they imply about the economic payoffs from marine reserves. We show that under a wide range of scenarios in terms of arrival rates and shock magnitudes that a marine reserve can increase resource rents even with identical shock sensitivities in the reserve and harvested populations. Our result is important because it holds true despite the fact that in all the simulations harvesting is optimal, the population is persistent, and there exists no management error or uncertainty over the size of the current population.

The intuition for our results is that reserves act as a ‘hedge’ in the presence of negative shocks that allow for a larger harvest immediately following a shock. Thus, the greater the size of a negative shock, the more frequent is its occurrence, and the larger is its effect on the harvested relative to the reserve population, the more valuable is a marine reserve and the bigger its optimal size.

#### (ii) Resource Rents and Harvest Trade-offs

We have shown that a reserve can generate an economic payoff to fishers, even with optimal harvesting, provided there exist negative shocks. These shocks reduce the return to fishers, but in the presence of such shocks a reserve provides a buffering effect that allows for a greater harvest after a shock, and thus higher resource rents than otherwise would be obtained. The trade-off is that, in the *absence* of any shocks, a reserve reduces the harvest obtainable with optimal harvesting. The nature of the harvest trade-offs is illustrated in Figure 1, assuming a negative shock in the fishery of 13 per cent and an arrival rate of every 25 years that generate an optimal reserve size of 26 per cent. For illustrative purposes in Figure 1 we set the shock frequency so that two negative 13 per cent shocks occur, one after another, so as to simulate the negative 13 per cent shocks that actually occurred in both 1964 and 1965 in the

FIGURE 1  
*The Difference in Harvest between the Case of Optimum Harvest with a 26 per cent Reserve and Optimum Harvest with no Reserve*



Pacific halibut fishery. Prior to the shocks in year 25 of our simulation, the amount harvested is *less* with a reserve, but immediately after the shock and for some time afterwards, the reserve provides a greater harvest.

The economic benefits of increased harvests immediately following a shock are subject to diminishing returns in terms of reserve size. This is shown in Tables 1–3 for any given negative shock and arrival rate. If there exists a positive optimal reserve size, the payoffs first increase, reach a maximum at the optimum size, and then decline with further increases in reserve size. In our simulations the initial population is of a given size, but we can show that the optimal reserve size (26 per cent) in the base case is invariant to the population's initial value.<sup>14</sup> In other words, our results about the economic payoffs from a reserve relative to the no-reserve case are not dependent

<sup>14</sup> In our simulations the steady-state population is invariant to the initial population. In other words, whether we rebuild or deplete the population, as we move towards the fluctuating steady state and *if* it pays to have a reserve of a fixed size, the optimal reserve size is identical in both cases. Figures that show this result are available from the authors on request.

on the initial population being below its steady-state value.

### (iii) Biological and Economic Parameters

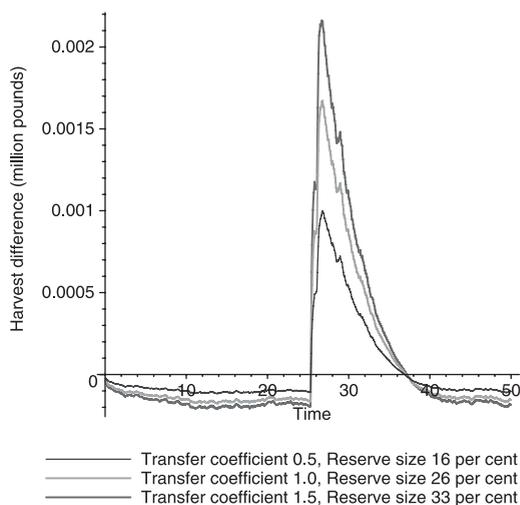
The economic payoffs from marine reserves in the presence of negative shocks depend on the relative size of both biological and economic parameters. In terms of the biology, the intrinsic growth rate ( $r$ ) and the transfer coefficient ( $\phi$ ) are major determinants of the economic value of a reserve. We note that the higher the intrinsic growth rate, the quicker the population can rebound following a negative shock. Thus, given that a reserve helps to increase the harvest immediately following a negative shock, we can show that the higher is the intrinsic growth rate the smaller is the optimal reserve size. In our simulations, if we change the estimated  $r = 0.2985$  by one standard deviation ( $\sigma = 0.03$ ), the optimal reserve size ranges from 24 per cent ( $r + \sigma$ ) to 28 per cent ( $r - \sigma$ ).

The transfer of fish from the reserve to the harvested population is also an important determinant of the economic payoffs from reserves, namely, the greater the number of fish that leave the reserve and become subject to exploitation, the less protection that is provided by a reserve of a given size (Roberts & Sargant, 2002). Thus, the greater is the rate of transfer from the reserve to exploited populations, the larger is the required reserve to provide a 'hedge' in the event of a negative shock. We can show that as we vary the transfer coefficient from 0.5 to 4.0 the optimal reserve size increases from about 16 to a little over 50 per cent of the total population given a negative 13 per cent shock in the harvested population with an arrival rate of every 25 years.<sup>15</sup>

Figure 2 shows the effects of different transfer coefficients on the harvest compared to the no-reserve case assuming the same magnitude and frequency of negative shocks that were applied in Figure 1. Each transfer coefficient corresponds to a different optimal reserve size where the greater the transfer coefficient, the larger the optimal reserve size. Compared to the no-reserve case, a larger transfer coefficient results in a lower harvest before the arrival of the negative shock, but generates a higher harvest immediately following the shock, and for some time thereafter. This illustrates the trade-off associated with increasing

<sup>15</sup> A figure that shows the relationship between optimal reserve size and the transfer coefficient is available on request.

FIGURE 2  
Harvest Difference between Three Optimal Reserve Sizes and No Reserve with Different Transfer Coefficients



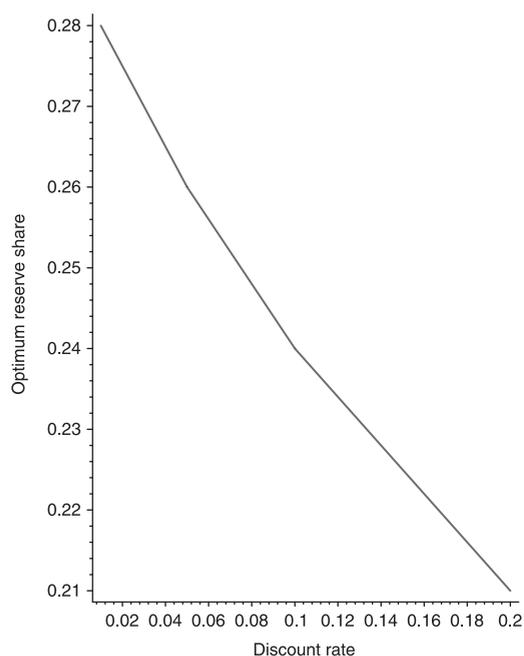
reserve size – more spillovers and a greater harvest following a negative shock, but a lower harvest in the absence of such a shock.

In the terms of resource rents, the lower is the discount rate, the greater the benefit from a reserve because the more valuable will be the future returns from a higher harvest immediately following a shock. Consequently, optimal reserve size and the economic payoff from a reserve are decreasing in the discount rate. This is illustrated in Figure 3 for an arrival rate of every 25 years and a negative shock of 13 per cent in the harvested population. Figure 3 also shows that, for the Pacific halibut fishery, the economic payoffs associated with a reserve are robust to changes in the discount rate. At a discount rate of about 20 per cent the optimal reserve size is close to 20 per cent, but even at a very high discount rate of 50 per cent it still pays to have a marine reserve in the base case, that is  $\psi(x_R) = 0$ ,  $\gamma(x_{NR}) = -0.13x_{NR}$ , with an arrival rate of every 25 years.

### (iv) Economic Payoffs from Marine Reserves

Our results provide a number of important insights when designing reserves for harvested populations subject to negative shocks. We found that reserves have a positive economic value under environmental uncertainty, even if harvesting is

FIGURE 3  
Relationship between Discount Rate and Optimum Reserve Size



optimal in the sense that we maximise the discounted resource rents, and the size and the probability of occurrence of shocks are known in advance. This payoff arises via spillovers from the reserve to the harvested population that allow for a greater harvest immediately following a negative shock, and also reduce the recovery time of the harvested population. The speedier recovery of the population explains the finding of several authors that marine reserves can lower harvesting variance and also population variance (Conrad, 1999).

We emphasise that our results are obtained without assuming management uncertainty over stock size (Lauck *et al.*, 1998), management errors in setting fishing effort, suboptimal harvesting or a minimum viable population. We also show that reserves can generate economic payoffs without requiring a low population level or assuming that the current harvest lowers recruitment (Gerber *et al.*, 2003: S58). Our simulations demonstrate that the larger the negative shock, the more frequent its occurrence and the larger the proportional impact on the harvested relative to the reserve

population, the greater the payoff from a reserve and the larger is its optimal size. These findings suggest that reserves can play an important role in raising fisher incomes in the presence of irreducible uncertainties (Ludwig *et al.*, 1993).

#### V Concluding Remarks

Using a stochastic bio-economic model that we develop and solve using a perturbation method, we show that a marine reserve can generate economic payoffs not previously identified in the literature. We find that even if harvesting is optimal, the population is persistent and there exists no uncertainty over the size of the current population, a marine reserve can increase resource rents and reduce the recovery time for a harvested population in the presence of negative shocks.

The reason a reserve has economic value is because it allows for spillovers of fish from the reserve to the harvested population following a negative shock that can, in turn, raise resource rents. In this sense, reserves act as a 'hedge' against negative shocks provided the sensitivity to the shock is not greater in the reserve than the harvested population. The trade-off with a reserve, however, is lower harvests and resource rents in the absence of such shocks.

Using data from the Pacific halibut fishery, which has one of the world's longest continuous records of stock size and harvests, we simulate the economic payoffs of a marine reserve with optimal harvesting under various scenarios regarding the size and incidence of negative shocks, and the relative impact on the reserve and harvested populations. We show that the larger the negative shocks, the more frequently they occur and the more they proportionally affect the harvested population, the larger will be the economic payoff from a marine reserve compared to no reserve, and the greater the optimal reserve size. We also find that spillovers from the reserve to the harvested population reduce the time it takes for the harvested population to recover following a shock that, in turn, can lower both the population and harvesting variance.

Our results show that in the presence of stochastic shocks marine reserves can generate economic benefits even if the population is neither initially overexploited or subject to extinction, and there exists no management error over the level of fishing effort or management uncertainty regarding the current population. Overall, our findings provide new insights into the benefits of marine reserves that should prove useful to those managing renewable

resources with uncertainty and designing reserves for fishery purposes.

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