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**Non-Market Values and Optimal Marine
Reserve Switching**

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Abstract

A stochastic bioeconomic model is constructed to analyze the effects of marine reserve ‘switching’ between a ‘no take’ area and a harvested area while accounting for both market and non-market values of the fishery. Using estimated parameters from the red throat emperor fishery from the Great Barrier Reef, simulations show that an optimal switching strategy is, under a range of scenarios, preferred to a fixed reserve and no reserve. Importantly, the results show that how non-market values change with the size of the fishery substantially affects both the returns from switching and the closure time.

JEL codes: C61; Q22;

Key words: Marine reserves; Stochastic control; Non-market values

1 Introduction

In the last two decades, the use of marine reserves has received increased attention as a strategy to solve management failures in fisheries. There is theoretical and some empirical evidence of the potential biological and socio-economic benefits from closing a fishing ground.¹ For instance, reserves may: 1) increase spawning biomass and population abundance; 2) improve habitat quality; 3) generate positive spillovers of larvae and/or fish from the reserve to harvested populations; 4) reduce the variation in biomass and catch; 5) enhance tourism and recreational activities; and 6) act as a hedge recruitment failure and unexpected variations in marine environments. These benefits, however, are highly dependent on marine reserve design.

Using stochastic dynamic programming we explore the problem of optimal marine reserve design from ‘switching’ or the closure period between establishing a reserve and its re-exploitation.² We compare the harvest and biomass with a reserve, with a fixed reserve, and with a reserve that can be optimally transferred into a harvested area. Given that reserves are frequently established for non-market values, such as maintaining biodiversity, we investigate the effect of different non-market value functions on the optimal switching regime. As far as we are aware, ours is the first study to develop such a model in the context of marine reserves.³

The contribution of this paper is to: (1) evaluate the payoffs of optimal marine reserve switching under uncertainty and (2) the effect of non-market value functions on the optimal switching interval. Key findings include: (1) the increased harvests associated with reserve switching in a range of scenarios, (2) differences in non-market value functions on the

closure time when switching and (3) the importance of non-market values on the returns from switching.

The paper is organized as follows. Section 2 develops a stochastic bioeconomic model of marine reserve switching, incorporating both the harvesting and non-market values of reserves. The model is applied to the red throat emperor fishery of the Great Barrier Reef. Section 3 describes the fishery and discusses the parameter values applied in this study. Section 4 simulates and contrasts the economic and biological outcomes of different policy scenarios ignoring any non-market value while section 5 explicitly evaluates the effects of three different non-market value functions on optimal switching. Section 6 provides concluding remarks.

2 The model

Biological model

(1) Space. Spatial features are modeled by a metapopulation model in which discrete patches represent a fish habitat and the size of patches is determined by the carrying capacity. As in other metapopulation models (for example, Sanchirico and Wilen 1999), this paper assumes that the distance between patches is identical and fixed, the size of each patch is constant, and the transfer function $T_{ij}(\mathbf{x})$ captures the various forms of fish dispersal processes between patches. Here, $\mathbf{x} = (x^1 x^2 \cdots x^3)$ denotes the vector of fish stocks, and $i, j \in N$ is the site index $N = \{1, 2, \dots, n\}$.

(2) Population dynamics. Time is discrete, indexed by t . The population dynamics in site $i, j \in N$ at time t are modeled as:

$$\begin{aligned}
x_{t+1}^i &= x_t^i - h_t^i + z_t^{gi} r x_t^i \left(1 - \frac{x_t^i}{K^i}\right) + \sum_j^{j \neq i} T_{ij}(x) - z_t^{si} x_t^i ; \text{ if site } i \text{ is open; and} \\
x_{t+1}^i &= x_t^i + z_t^{gi} r x_t^i \left(1 - \frac{x_t^i}{K^i}\right) + \sum_j^{j \neq i} T_{ij}(x) \text{ if site } i \text{ is closed.}
\end{aligned} \tag{1}$$

where x_t^i is the fish stock and K^i is the carrying capacity in site i . The term $x_t^i - h_t^i$ is the escapement in each period. If site i is a fishing ground, the fish stock is exploited by the harvest level $h_t^i > 0$, whereas $h_t^i = 0$ if a reserve is placed on the site. The second term represents the density dependent stock-recruitment relationship with the intrinsic growth rate r . The third term is the fish transfer function. The last term z_t^{si} represents stochastic variations in fish growth at site i (growth uncertainty). The term z_t^{si} is a large negative shock that is proportional to the fish stock that is only realized in fishing grounds to represent the higher risk of habitat destruction and stock-recruitment failure in a fishing ground (Goñi 1998; Turner et al. 1999; Jennings et al. 2001).

(3) Uncertainties. The growth uncertainty is specified as $z^g = 1 + (2u - 1)\varepsilon$, where u is a uniformly discretized grid. The term ε determines the size of variations and lies between 0 and 1, indicating from 0 to 100 per cent variation. It is assumed that z^g follows a Markov process with the same transition probabilities between each state. The large negative shock z^s is specified as:

$$z_t^s(\omega_t) = \begin{cases} 0 & \text{if } \omega_t = 1 \text{ (shock is not realized)} \\ \alpha & \text{if } \omega_t = 2 \text{ (shock is realized)} \end{cases} \tag{2}$$

If the indicator variable ω_t is 2 at time t , then the negative shock is realized, otherwise there is no shock. The size of the negative shock is proportional to the stock level that is determined by parameter α .

(4) Transfer function. The transfer function captures the characteristics of fish flow from one site to another. Fish dispersal is important because the spatial features and the policy implications of marine reserves significantly depend on the linkages between sites (Sanchirico and Wilen 2001; Sanchirico et al. 2006; Smith et al. 2009). In a closed process, there are no interactions between sites and the biomass in each site is determined only by its own growth and harvest rate. In this case, should the local population fall below a minimum critical threshold it will be extirpated. In a fully integrated open process each site is interconnected. This allows temporary local extinction of the fish stock as well as stock recovery through fish transfer from another site.

We assume that the fish flow depends on the relative density of the biomass between the two sites. Following previous studies (for example, Conrad 1999; Sanchirico and Wilen 2001; Grafton et al. 2006), the transfer function is specified as:

$$T_{ij}(x) = mK^i \left(\frac{x^j}{K^j} - \frac{x^i}{K^i} \right) \text{ if } i \text{ and } j \text{ are adjacent} \quad (3)$$

where m is the transfer coefficient. Assuming that the size of each site is identical, the transfer function can be reduced to $m(x^j - x^i)$. In this case, the transfer coefficient, m , represents the migration rate, that is, the fraction of the difference in biomass between sites i and j .

Economic model

Suppose that $\Gamma \subseteq N$ is a set of the sites that are open for fishing. Thus, the net profit at time t is defined as:

$$\pi_t^{np} = p(h_t)h_t - \sum_{i \in \Gamma} c(x_t^i)h_t^i \quad (4)$$

where $h = \sum_{i \in \Gamma} h^i$, $p(\cdot)$ is the inverse demand function, and $c(\cdot)$ is the cost function. The inverse demand and cost functions are defined respectively as:

$$p(\cdot) = \bar{p}h_t^{-1/\delta} \text{ and } c(\cdot) = \bar{c} / x_t^i \quad (5)$$

where $c_x < 0$, $c_{xx} > 0$, δ is the constant price elasticity of demand, and \bar{p} and \bar{c} are parameters. The demand function allows for various demands such that if $0 < \delta < \infty$ then $p_h < 0$ and the demand curve is downward sloping but if $\delta \rightarrow \infty$, the price is constant.

Policy Rule

The location of a reserve is the control variable. The harvest level is sub-optimally controlled by setting a ‘rule-of-thumb’ total allowable catch (TAC). In the presence of various forms of uncertainty, a constant escapement policy is not likely to be the optimal harvesting strategy, but the policy function is a function of the biomass (Sethi et al. 2005). Thus, we employ a feedback control policy where the harvest in each patch is a fraction of the biomass. In other words $h_t^i = \theta x_t^i$ if $i \in \Gamma$, but $h_t^i = 0$ if $i \notin \Gamma$.⁴ By varying the value of θ the effect of different levels of harvest pressure can be analyzed.

Non-market value of reserves

An important issue regarding marine reserves is the non-market value of closing a fishing area. Several studies estimate the value of marine reserves by incorporating non-market valuation methods. Bhat (2002), for example, estimates that reserve-induced reef quality improvements could increase the use values of a reserve in Florida Keys of the U.S. by 69 per cent. Kragt et al. (2009) estimate a recreational demand curve in the Great Barrier Reef and show that the welfare loss due to environmental degradation is substantial.

We suppose that the non-market value of marine reserves is a function of a weighted average of the population density in a protected area and the length of closure of a fishing ground. In other words, $\Phi = \alpha_3 \cdot (x / K) + (1 - \alpha_3) \cdot \tau$ where $\alpha_3 \in [0,1]$ is a weighting parameter and $\tau \in \{0,1,2,\dots\}$ is the period of site closure. To make the two terms, x / K and τ , consistent we redefine τ on the $[0,1]$ interval such that $\Phi \in [0,1]$ and assume $\alpha_3 = 0.5$. The non-market value function is defined as:

$$\pi^{nmkt}(\Phi_t) = \frac{\alpha_0}{1 + \exp(\alpha_1 - \alpha_2 \Phi(x_t, \tau_t))}, \quad \alpha_0, \alpha_1, \alpha_2 > 0 \quad (6)$$

Equation (6) is a logistic function where $\partial \pi^{nmkt} / \partial \Phi > 0$. The parameter α_0 represents the maximum value of π^{nmkt} . The parameters α_1 and α_2 , respectively, determine the curvature of the function and the time to achieve the maximum value. Given this functional form, the non-market value of reserves initially increases in a progressive way as Φ rises, but the rate of increase diminishes when the value approaches its maximum value.

Dynamic optimization model

The regulator's optimization problem is to maximize the sum of the discounted net profit from exploiting the fish stock and the non-market value of creating a reserve over time, that

$$\text{is, } \sum_t \pi_t^* = \sum_t (\pi_t^{np} + \pi_t^{nmkt}).$$

For tractability we consider a case with two sites, and suppose that site 1 is initially closed.

$$\begin{aligned} & \max \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \pi_t^* \\ & \text{subject to } \begin{cases} x_{t+1}^1 = x_t^1 + z_t^{g1} r x_t^1 \left(1 - \frac{x_t^1}{K^1} \right) + m(x_t^2 - x_t^1) \\ x_{t+1}^2 = x_t^2 - h_t^2 + z_t^{g2} r x_t^2 \left(1 - \frac{x_t^2}{K^2} \right) - z_t^{g2} x_t^2 - m(x_t^2 - x_t^1) \\ x_0^i = x^i(0), z_0^{gi} = z^{gi}(0) \text{ and } z_0^{si} = z^{si}(0), i = 1, 2 \end{cases} \quad (7) \end{aligned}$$

The Bellman equation is:

$$V(\mathbf{x}_t \mathbf{z}_t^g \mathbf{z}_t^s) = \max \left\{ \pi^*(x_t^2) + \beta \mathbf{E}_0 V(\mathbf{x}_{t+1} \mathbf{z}_{t+1}^g \mathbf{z}_{t+1}^s), \pi^*(x_t^1) - \kappa(\pi^*(x_t^2)) + \beta \mathbf{E}_0 V(\mathbf{x}_{t+1} \mathbf{z}_{t+1}^g \mathbf{z}_{t+1}^s) \right\} \quad (8)$$

where $\beta \in (0,1)$ is the discount factor, \mathbf{E}_0 is the mathematical expectation operator, and \mathbf{x} , \mathbf{z}^g , and \mathbf{z}^s denote, respectively, the vectors of the fish stock, stochastic variations in fish growth and the negative shock. The term $\kappa(\cdot)$ is the transaction cost function of rotating the reserve and is an increasing function of the foregone profit by closing the area ($d\kappa/d\pi^{*i} > 0$). Thus, the opportunity cost of closing a fishing ground increases with the foregone profit of fishing in the area such that the larger is κ_0 the higher is the transaction

cost. We assume that the cost is proportional to the profit, thereby, $\kappa(\pi^{*i}) = \kappa_0 \pi^{*i}$ and $\kappa_0 \in [0,1]$.

The value function $V(\cdot)$ represents the maximum attainable objective function at time t . The first term on the right hand side of the equation, $\pi^*(\cdot)$, is the total return if site 1 is continuously closed. The following term $\beta \mathbf{E}_0 V(\cdot)$ represents the discounted expected value function at time $t+1$. The first expression, $\pi^*(\cdot) + \beta \mathbf{E}_0 V(\cdot)$, is the overall total return when site 1 is closed. The second expression, $\pi^*(\cdot) - \kappa(\cdot) + \beta \mathbf{E}_0 V(\cdot)$, represents the overall total return when the reserve is rotated from site 1 to 2.

Computational method

Due to the complexity of the model, an analytical solution of the optimization problem is not obtainable. Thus, the problem is numerically solved by approximating the value function with the collocation method.⁵ In other words $V(\mathbf{x}, \mathbf{z}^g, \mathbf{z}^s) \approx \sum_{l=1}^L k_l \phi_l$ where ϕ is a degree L polynomial basis function with coefficients k , and,

$$V(\mathbf{x}_t, \mathbf{z}_t^g, \mathbf{z}_t^s) \approx \max \left\{ \pi^*(x_t^2) + \beta \sum_{l=1}^L \sum_{m=1}^M \sum_{q=1}^Q \omega_m^g \omega_q^s k_l \phi_l(\mathbf{x}_t, \mathbf{z}_t^g, \mathbf{z}_t^s), \right. \\ \left. \pi^*(x_t^1) - \kappa(\pi^*(x_t^2)) + \beta \sum_{l=1}^L \sum_{m=1}^M \sum_{q=1}^Q \omega_m^g \omega_q^s k_l \phi_l(\mathbf{x}_t, \mathbf{z}_t^g, \mathbf{z}_t^s), \right\} \quad (9)$$

where ω_m^g and ω_m^s are the probabilities of the realization of each state in the growth uncertainty and negative shock, respectively. Growth uncertainty z^g is discretized with 10 grids ($M=10$) and the negative shock z^s is discretized with two grids ($Q=2$) with the 5 degree Chebyshev polynomials as the basis function ($L=5$).

3 Red throat emperor fishery in Australia

The dynamic model is applied to the red throat emperor fishery in the Great Barrier Reef (GBR) of Queensland, Australia. The red throat emperor (*Lethrinus miniatus*) is one of the most important and major targeted species for both the commercial and recreational sectors. The fishery is managed by setting the total allowable catch (TAC) with individual transferable quotas (ITQs) for the commercial catch and also by minimum legal size regulations (Leigh et al. 2006). An important feature of this fishery is that it operates entirely within the Great Barrier Reef World Heritage Area (GBRWHA) such that the park's regulator also imposes spatial management controls including temporary and permanently closures of the fishing grounds (Williams 2003).

Figure 1 shows the changes in catch and catch per unit of effort (CPUE) of the fishery over time. The annual catch increased approximately four times between 1980 and 2003 while the catch per unit of effort dropped dramatically in the mid 1990s.⁶

[Figure 1 is about here]

To simulate the dynamic model, the values for the biological parameters are obtained from Leigh et al. (2006). The intrinsic growth rate (r) is 0.12 and the carrying capacity (K) is 6,913 tonnes. The landed price of red throat emperor is relatively stable at around US\$3,500 per tonne⁷ and we assume that the elasticity of demand is infinite with a price parameter equal to 5. In the absence of sufficient data, the parameters in the cost function and transfer coefficient are initially set at $\bar{c} = 2$ and $m = 0.1$ but detailed sensitivity

analysis of changes in these parameters is undertaken. The harvest fraction is set at $\theta = 0.08$, and the effect of changes in the parameter is also tested. The parameter for growth uncertainty is $\varepsilon = 0.05$, the arrival rate of the negative shock is 0.04 and the size of the shock is set at $\alpha = 0.13$. The discount rate is, initially set at 10 per cent ($\beta = 0.9$).

4 The value of marine reserves switching (without non-market values)

Initially, we simulate the economic and biological values associated with marine reserves switching without accounting for non-market value of reserves.

Harvest and biomass under different policy scenarios

The density distribution of the biomass and harvest are presented in Figure 2 for three policy scenarios: temporary (or switched) reserve, a spatially fixed reserve and a no-reserve. The figure shows that a reserve produces a much higher biomass than no reserve in the presence of negative shocks. It also illustrates two important functions of a marine reserve. First, it is a buffer against stochastic variations and second, the spillovers from the reserve to harvested populations smooth the average biomass over all sites. As a result, the management with reserves generates a smaller variance in both the biomass and harvest. These two effects combined allow the total harvest in the reserve case to exceed the no-reserve case given sufficiently large negative shocks to the fishery. This result is consistent with the findings in previous studies, such as Lauck et al. (1998); Grafton et al. (2006); Costello and Polasky (2008).

Although the biomass difference between a fixed reserve and a temporary reserve are not large in these simulations, the biomass is higher in the fixed reserve case. By contrast, the harvest is greater in the switching strategy because the highest growth rates are at

intermediate values of the biomass. Thus, the switching strategy generates a greater catch but with a smaller biomass than the fixed reserve case.

[Figure 2 is about here]

The density distribution of the biomass and harvest for the three policy scenarios when there are *no* fish spillovers ($m = 0$) are compared in Figure 3. The density distribution of the biomass is similar to that under the open process as presented in Figure 2. The management with reserves generates a higher biomass than the no-reserve case. The biomass in the fixed reserve case is also likely to be greater than that in the switching strategy. The fishing ground is rotated to a more profitable area in the switching strategy and, as a result, the total fish stocks are more exploited than the fixed reserve case. While there is no spillover effect in the closed process, the reserve still works as a buffer against stochastic variations. As a result, the variations in the biomass and harvest in the management with reserves become smaller than those in the no-reserve case.

Without a spillover effect from the reserve to harvested populations, the reserve no longer smooths the average biomass over sites. No spillovers mean that the harvest in the fixed reserve case is much lower than that in the no reserve and temporary or switched reserve cases. Further, without a reasonable volume of fish flow, the total exploitable population becomes significantly small in the fixed reserve case. In other words, when there are only weak linkages between sites, a large trade-off exists between the harvest and biomass with a fixed reserve. However, the switching strategy can decrease the degree of this trade-off. By rotating a non-fishing area over time, the switching strategy maintains a relatively high catch level as well as fish stocks, even if there are only weak linkages between adjacent sites.

[Figure 3 is about here]

Sensitivity analysis – biological and economic parameters

The difference in policy outcomes between various scenarios depends on the relative size of the biological and economic parameters. The biomass is the highest in the fixed reserve case and the smallest in the no-reserve case. Simulations with different values of the biological and economic parameters show that this relationship in the biomass holds for all possible values used in the model, whereas the relationship in the harvest is not straightforward.

We analyze how the harvest in different policy scenarios changes with different values of the transfer coefficient (m), harvest fraction (θ), harvesting cost (c), the time discount rate (β), and the size of negative shocks (α). Monte Carlo simulations generate 10,000 sets of time series of the harvest for different values of the parameters, and we subsequently compute the difference in the average harvest between each policy scenario. The results are summarized in Table 1.⁸

[Table 1 is about here]

Table 1 shows that the greater is the transfer coefficient (m), the larger is the harvest with a reserve (both switching and fixed reserve cases) compared to no reserve. This is because the positive spillovers from the reserve to harvested populations are determined by the connectivity between adjacent sites. Consequently, the benefit of marine reserves depends critically on the fish transfer coefficient (m) such that without sufficient positive spillovers from the reserve to harvested populations, the reserve would decrease the total

exploitable population and, in turn, the overall harvest. This is particularly the case, as shown in Figure 3, if the reserve is permanently fixed at one location.

The results in Table 1 indicate that the greater is the harvest fraction (θ) the larger is the harvest with a reserve than with no reserve. This is because if fish stocks are heavily exploited, the marginal benefit of positive spillovers from the reserve to the harvested populations increases. In other words, the greater is the harvest fraction, the larger is the closed area necessary to compensate for the greater reduction in biomass. Where the harvest difference between the switching and fixed reserve cases is compared, there is a positive relationship between the value of the harvest fraction and the harvest difference. In the switching strategy, the fishing ground is rotated to a more profitable area over time and this consequently produces a greater harvest. However, as shown in Figures 2 and 3, the greater harvest subsequently leads to a smaller biomass in the switching strategy than in the fixed reserve case.

The optimal switching rule depends on the profitability from harvesting fish stocks. Thus, the price-cost ratio, in part, determines the optimal frequency of switching a reserve. For instance, when the harvesting cost (c) increases, the net profit becomes more sensitive to a decline in the fish stock. Therefore, the greater the harvesting cost, the higher the frequency of rotating the fishing ground to a new site where fish stocks are relatively more abundant. In other words, as harvesting costs increase, the switching strategy produces a greater harvest than the other two policy scenarios.⁹

The time discount rate (β) is a weighting parameter that represents the relative importance of the current and future benefits from the fishery. Table 1 shows that if the time discount rate decreases (β increases), the harvest difference between the switching

and no-reserve cases increases. This is because the lower the discount rate, the greater the marginal benefit of the spillovers from the reserve to harvested populations. Table 1 also shows that the lower is the discount rate, the higher is the frequency of switching a reserve, and, as a result, the harvest difference between the switching and fixed reserve cases becomes greater.

In terms of the size of the negative shock (α), Table 1 shows that the larger is the size of the shock the greater is the harvest with a reserve than with no reserve. This is because spillovers from the reserve to the harvested population accelerate the stock recovery process following a negative shock.¹⁰ This resilience created by a reserve is further enhanced with the size of the negative shock. Thus, the cost of creating a reserve decreases with the size of the shock. This result is also illustrated in the density distribution of the harvest in Figure 4. The figure shows that, with a relatively small size of negative shocks ($\alpha = 0.05$), the total harvest with a reserve is smaller than the no reserve case. However, with a relatively large negative shock ($\alpha = 0.21$), the mean harvest with a reserve is greater than in the no-reserve case.

Table 1 also shows that the larger is the size of the negative shock (α), the greater is the harvest difference between the switching and fixed reserve cases. In the switching strategy, once the harvested population declines significantly following a shock, the area is closed for stock recovery. In the meantime, the fishing ground is rotated to a more stock abundant area and, as a result, the harvest in the switching strategy becomes greater than in the fixed reserve case. Figure 4 also shows that, when the size of the negative shock is relatively large ($\alpha = 0.21$), the total harvest is greater in the switching strategy. By contrast, when the

size of the negative shock is relatively small ($\alpha = 0.05$), switching a reserve is not optimal, and hence the harvest in the switching and fixed reserve cases are identical.

[Figure 4 is about here]

Switching and negative shocks

The economic benefit from switching a reserve is greater in the presence of large negative shocks. To see this result in more detail, Figure 5 illustrates the relationship between the negative shock and the effect of switching a reserve over time. In the figure, a negative shock arrives at time one, and, in the switching strategy, the reserve is correspondingly rotated to a new area. However, in the fixed reserve case the ‘no-take’ area is constant.

In the switching strategy, a fishing area is rotated to the previously closed area where fish stocks are relatively more abundant, following the shock. As a result, the harvest difference between the switching and fixed reserve cases becomes much larger in the short run. At the same time, the short-run increase in the harvest produces a smaller biomass in the switching strategy than in the fixed reserve case. Thus, after the short-run ‘spike’, the harvest difference becomes negative for a certain period. This is particularly so if the size of the shock is large. In other words, the larger is the size of the negative shock, the greater is the short-run increase in the harvest difference with switching, but also the longer is the period that the harvest difference remains negative following the short-run ‘spike’. For all cases, the harvest difference eventually approaches zero as fish stocks recover to the steady-state level. Figure 5 illustrates this trade-off between the long-run and short-run harvest with a switching reserve strategy.

5 Non-market value of a reserve

An issue unexplored in the economic literature until now is how the optimal switching rule changes after consideration is given to the non-market value of marine reserves. In this case, the regulator's objective is to maximize total returns (the sum of the expected discounted net profit and non-market value) rather than the net harvesting profit. To investigate how the optimal switching rule and its policy outcomes change depending on different characteristics of the non-market value of reserves, we consider three different types of a non-market value function that are illustrated in Figure 6. In the Type 1 case, the non-market value of reserves reaches the maximum value with a relatively small biomass and short closure period (i.e., a relatively small value of Φ). In the Type 2 case, the non-market value rises to the maximum value with a relatively small value of Φ , but the maximum value is greater than in Type 1. In the Type 3 case, the maximum value is the same as Type 2, but it requires a higher biomass and a longer closure period of a fishing area to realize this maximum value.

Table 2 summarizes the mean value of the objective function for three different types of policy scenarios with the three types of the non-market value function. The table shows that the payoff is the smallest with a fixed reserve without harvesting. In this case, the higher non-market values are not sufficient to offset the losses from no harvesting. By contrast, the mean value of the objective function is the largest in the switching strategy although this result is dependent on the parameters used in the simulations and the chosen non-market value functions.

Total returns, switching and negative shock

Figure 5 shows that, following a shock, switching the reserve increases the harvest in the short-run by rotating the fishing ground to a new area. However, due to the trade-off between the harvest and biomass in switching a reserve, the harvest difference also becomes negative for a certain period after the short-run ‘spike’. When the non-market value of reserves is included in the objective function, switching the reserve *decreases* both the total biomass and the non-market value. Thus, when the non-market value is taken into account in the decision process, the trade-off between the short-run and long-run harvest in switching a reserve *increases*.

Figure 7 illustrates the difference in total returns between the switching and fixed reserve cases over time following a large negative shock. The figure shows that if the non-market value of a reserves rises to the maximum value relatively quickly, such as for Types 1 and 2 in Figure 6, then the decrease in the non-market value from switching is relatively small. By contrast, if it requires a longer closure period and a higher biomass to realize the maximum non-market value of reserves (Type 3 in Figure 6), the short-run ‘spike’ becomes smaller than in the previous cases. Moreover, there is a much longer period where the difference in the total returns is negative after the short-run ‘spike’. In sum, with a Type 3 non-market value function, the overall benefit from switching a reserve is reduced compared to the benefits obtained from Types 1 and 2.

Optimal frequency of switching

Table 3 illustrates the optimal frequency of switching in four different cases. Monte Carlo simulations generate 10,000 sets of time series of the control variable and the optimal frequency of switching is computed for each set of time series. The table shows that, when the non-market value of reserves is not taken into account, the reserve is rotated 3.53 per

cent of the total period. However, after the non-market value of reserves is included, the optimal frequency of switching is reduced. This is because although switching the reserve increases the harvest in the short-run, following a negative shock, it also decreases the total return after the short-run ‘spike’. The degree of this trade-off differs depending on the type of the non-market value function. Consequently, the optimal frequency of switching also varies between different types of the function.

Table 3 shows that the optimal switching frequency is the highest with the Type 1 case and the lowest with the Type 3 case. For the Type 1 case, the maximum non-market value is relatively low and is realized with a smaller biomass and shorter closing period than the other two types. Thus, the foregone non-market benefit from rotating a reserve is less than the other two types. By contrast, in the Type 3 case the maximum value is relatively large but it also requires a higher biomass to achieve this level. As a result, it requires a longer closure period to realize the maximum value. Thus, the foregone benefit from switching the reserve is greater, and, as a result, the optimal frequency of switching is less than with the other two types.

6 Concluding remarks

Marine reserves are receiving increased attention as a policy instrument to solve management failures in fisheries. Previous studies have found that under certain conditions reserves will provide a win-win solution, namely, both the biomass and harvest can be greater than without reserves in the presence of negative shocks. While this literature provides important insights into the design of optimal reserve management, until now, there has been no model to determine whether and when non-fishing areas should be

rotated over time or to evaluate the effect of non-market values on returns and reserve switching.

To address these crucial gaps in marine reserve design, a stochastic bioeconomic model is developed to analyze a marine reserve switching strategy while accounting for both market and non-market values of a fishery. Applying the model to the red throat emperor fishery in the Great Barrier Reef, the results show that optimal switching strategy can maintain a relatively high catch and biomass, even if there are only weak linkages between sites. By contrast, if sufficient spillovers from the reserve to harvested populations were not generated, fixing the non-fishing area at one site could substantially decrease the total harvest. Thus, when the transfer rate is small a strong trade-off exists between the harvest level and the biomass in the fixed reserve case. However, switching a reserve into a harvested area reduces this trade-off. The findings indicate that although the switching strategy produces a higher catch, it also results in a smaller biomass than the fixed reserve case. The results also show that the optimal closure time with switching depends crucially on the size and the arrival rate of negative shocks.

A key contribution of the modeling is the finding that the optimal frequency of switching decreases if the non-market values are accounted for in the decision process. Switching the reserve is, however, optimal if the maximum non-market value is relatively low and if this value is realized within a short closure time and by a relatively small biomass. If the economic payoff from non-fishing activities is significantly large and/or if it is difficult to achieve the non-market value, switching is less likely to generate extra payoffs than a fixed reserve.

Overall, the results show that under a wide range of scenarios it is optimal to rotate a non-fishing area from one site to another, especially if the fish migration rate is low and if large negative shocks exist in the environment. An optimal switching strategy offers the possibility of maintaining both high catch level and fish biomass, but it also requires detailed knowledge of the population dynamics and the environment coupled with appropriate monitoring and evaluation.

Endnotes:

1. There are a large number of previous studies on marine reserves. Comprehensive literature reviews are provided by for example Guenette et al. (1998), Hilborn et al. (2004) and Grafton et al. (2005).
2. There are few but important previous studies looking at temporary fishing closures. For example see Hilborn and Walters (1992), Guénette et al. (1998) and Costello and Polasky (2008). Costello and Polasky (2004) also study the dynamic site selection problem on protecting biodiversity but not in the context of marine reserves.
3. By contrast, the effects of non-market value on forest rotation are well studied (Hartman 1976; Swallow et al. 1997).
4. A similar specification is utilized in a recent study on fishery profits of marine reserves (White et al. 2008).
5. See Judd (1998) and Miranda and Fackler (2002) for the technical details.
6. Leigh et al. (2006) estimate that the exploitable biomass fell to approximately 60 per cent in the late 1990s.

7. We use the exchange rate A\$ 1.00 = US\$ 0.70
8. Figures that illustrate how the harvest difference between different policy scenarios changes with each of these parameters are available from the authors on request.
9. It is important to note that the findings here are related to the optimal reserve size – the greater is the harvesting cost the larger is the optimal reserve size (Grafton et al. 2006). This is because, the higher the harvesting cost, the more sensitive the profitability of a fishery to a decline in the fish stock. Thus, as the harvesting cost increases, the optimal size of a reserve is greater for stock recovery through the spillovers from the reserve to harvested populations.
10. This result is consistent with the findings in Grafton et al. (2006).

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Table 1 Effect of marginal increase in parameter values on the harvest difference between different policy scenarios¹

	m	θ	c	β	α
Harvest difference between switching and no-reserve	+	+	+	+	+
Harvest difference between fixed reserve and no-reserve	+	+	n/a^2	n/a^2	+
Harvest difference between switching and fixed reserve	-	+	+	+	+

1. A (+) indicates that a marginal increase in the given parameter value, holding everything else constant, will increase the harvest difference between the two management scenarios, while a (-) indicates it will decrease the harvest difference.

2. The signs in these cells cannot be determined due to the model structure. However, from the insights of Grafton et al. 2006, we conjecture that these signs are both positive.

Table 2: Mean values of the objective function under different policy scenarios

	Switching	Fixed reserve	Fixed reserve with no harvest
Type 1	2099	1704	448
Type 2	2529	2150	896
Type 3	1748	1376	250

Table 3: Optimal frequency of switching ($m = 0.1$ and $\theta = 0.08$)

Without non-market value		With non-market value		
		Type 1	Type 2	Type 3
Mean	0.0353	0.0198	0.0156	0.0139
Max	0.15	0.1	0.08	0.07
Min	0.01	0.01	0.01	0.01

Figure 1 Catch and CPUE over time of the red throat emperor fishery

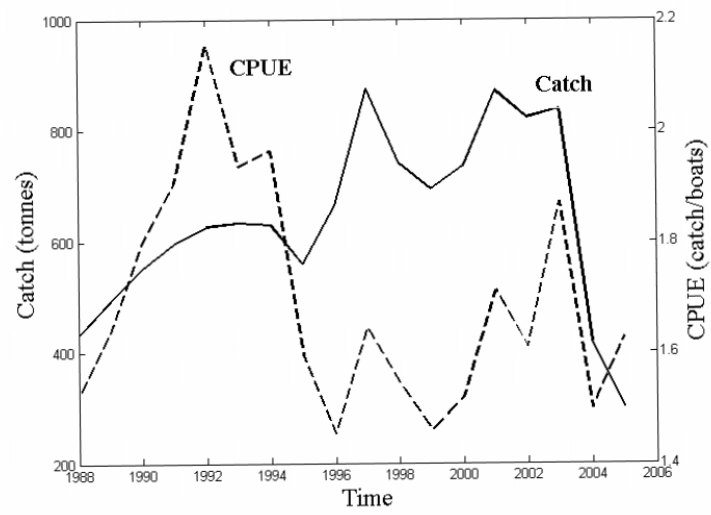


Figure 2 Density distribution of biomass and harvest with spillovers ($m=0.1$ and $\theta=0.08$)

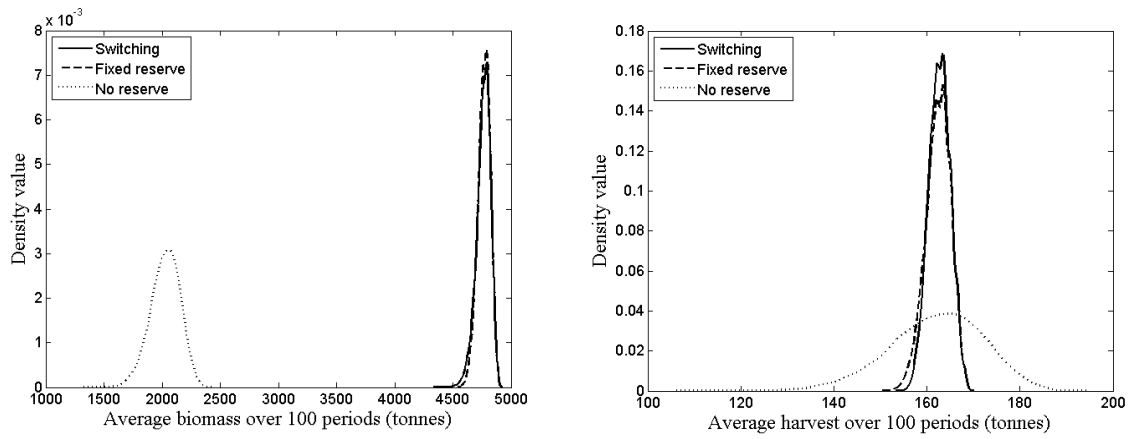


Figure 3 Density distribution of biomass and harvest with no spillovers
 ($m = 0$ and $\theta = 0.08$)

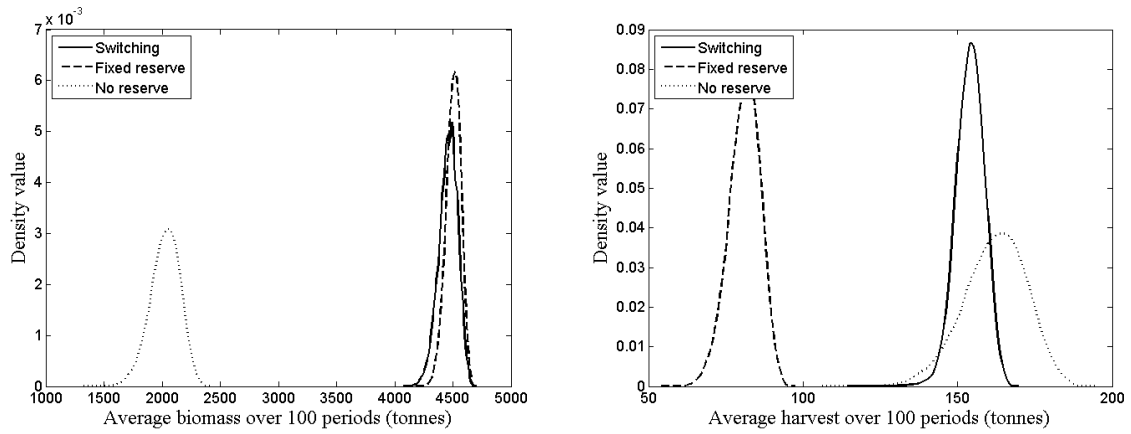


Figure 4 Sensitivity analysis: density distribution of harvest with different sized negative shocks

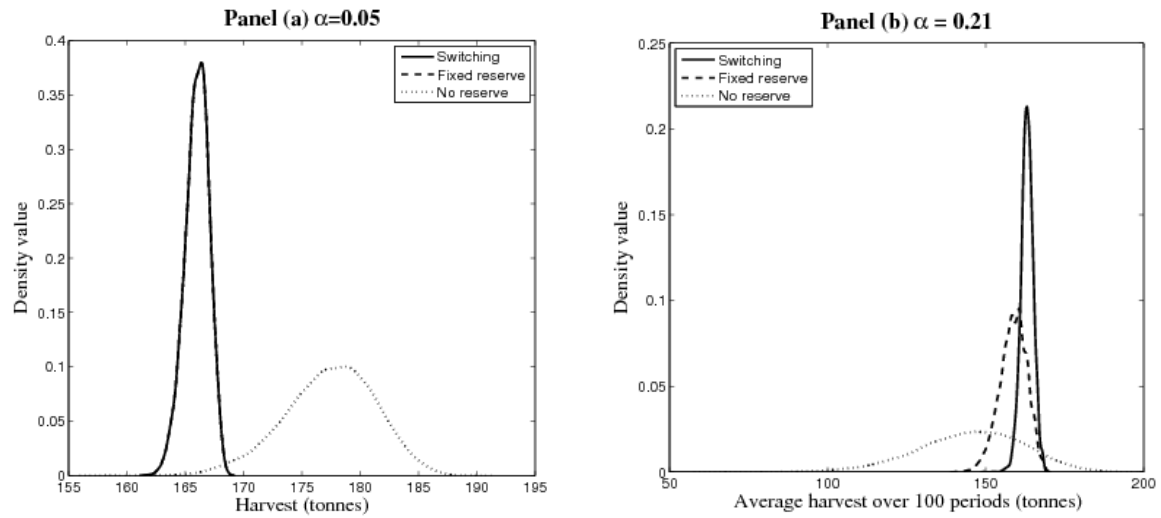


Figure 5 Difference in harvest between fixed and switching strategies with different sized negative shocks

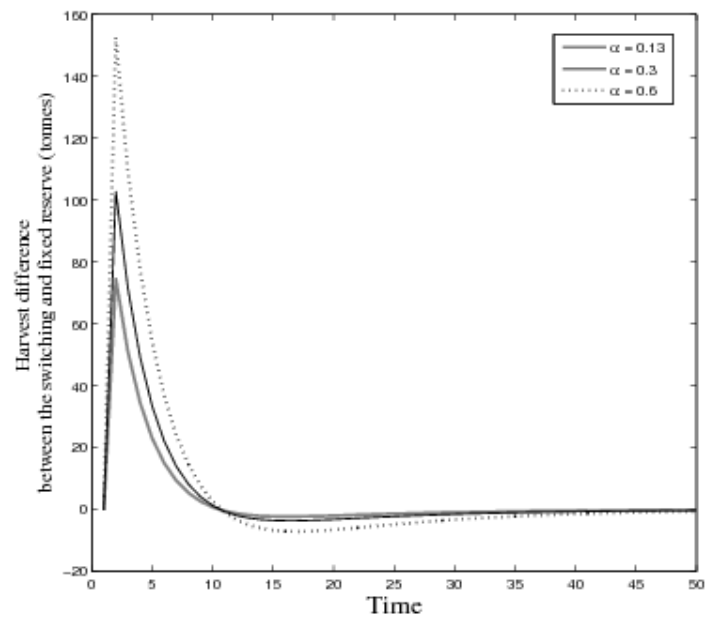


Figure 6 Three types of non-market value functions

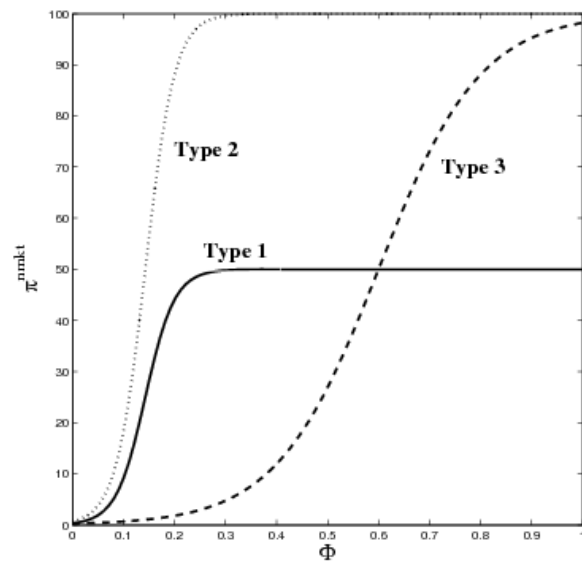


Figure 7 Difference in total returns between fixed and switching strategies with different sized negative shocks and non-market values

