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Bioeconomic analysis of protected area use in fisheries management*

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Protected areas in fishery management have been suggested to hedge management failures and variation in harvests. In this paper, a stochastic bioeconomic model of a two-species fishery in the Manning Bioregion is used to test the performance of protected areas as a management tool in a fishery. The establishment of a protected area is analysed under the assumption of heterogenous environments that are linked via density-dependent or sink-source stock dispersal relationships. The sensitivity of the results to different degrees of management is also explored. The model is applied to the Ocean Prawn Trawl, and Ocean Trap and Line fisheries within Manning Bioregion in New South Wales, Australia. The focus of the study is placed on the biological and institutional characteristics that yield benefits to the fishery. It was found that protected area use in the Manning Bioregion is likely to have differing effects on the two fisheries examined, benefiting Ocean Trap and Line fishers but adversely affecting Ocean Prawn Trawl fishers. Overall, it is unlikely that protected area use will lead to an increase resource rent in the fishery.

Key words: bioeconomics, fisheries management, marine protected areas.

1. Introduction

Various justifications for marine protected area use in fisheries have been suggested. For example, marine protected areas have been suggested as a means to manage uncertain events that can cause fisheries to collapse (Grafton and Kompas 2005). Grafton *et al.* (2005a) provide examples of the Peruvian *anchoveta* fishery, which collapsed after an *El Nino* event, and the Canadian Northern Cod Fishery, which suffered a similar fate after a negative shock in the 1980s for which protected areas could have been used to mitigate fishery collapse. It was suggested that as stocks within protected areas have the potential to provide a buffer source for the surrounding fishery (Lauck *et al.* 1998) the probability of a collapse could have been reduced.

Recently, the New South Wales (NSW) Government has committed to the establishment of a representative system of marine parks. The aim is to

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protect elements of the unique marine habitats that span the NSW coast. Although the focus for protected area establishment is not to manage fisheries, and thus, the structure of the park will be different to what is required for use as a management tool (Grafton *et al.* 2005b), they are likely influence fishery outcomes. In 2004, an assessment of the Manning Shelf Bioregion (an area that spans north of the Hunter River to north of Nambucca Heads) was completed. It identified an area between Stockton Beach and Wallis Lake as the most likely area for a new marine park (Breen *et al.* 2004, p. 105).

The purpose of this paper is to examine the potential impacts of such a marine protected area on the fishing industry. A stochastic version of the model presented in Greenville and MacAulay (2006) is developed and applied to the two main fishing activities in the region. The sensitivity of the results to dispersal is also examined through considering both density-dependent dispersal patterns (movements of biomass between areas that are driven by differences in relative densities) and sink-source dispersal patterns (movements of biomass that occur in one direction).

The remainder of this paper is organised as follows. In Section 2, the arguments for marine protected area use in fisheries management are provided, with the bioeconomic model used to test protected area creation discussed in Section 3. An overview of the commercial fishing industry in part of the Manning Bioregion is provided in Section 4. Model calibration and results are provided in Sections 5 and 6 with a discussion of the policy implications and concluding comments in Sections 7 and 8.

2. Marine protected areas

Results obtained from the bioeconomic analysis of marine protected areas vary. Protected areas used in open-access fisheries exploiting single stocks have been shown to benefit both fishers and society (Sanchirico and Wilen 2000). Under the assumptions that increases in biomass are a gain to conservationists, and increases in harvests a gain for fishers, Sanchirico and Wilen (2000, 2001) defined a potential 'win-win' outcome. The authors showed that if pre-reserve harvest equilibrium existed, under certain conditions relating to cost of effort and biomass migration, the establishment of a marine protected area would yield a win-win outcome. Some authors, however, have suggested that in these circumstances, the ability of protected areas to achieve their conservation objective is questionable due to a concentration of effort in the remaining area (Hannesson 2002).

Under limited entry conditions the potential for a protected area to lead to a win-win outcome is reduced. Sanchirico and Wilen (2000) argue that the establishment of a protected area would require a reduction in the level of effort expended. In a multipatch fishery, this loss could be minimised with the closure of multiple patches (Sanchirico 2005). Despite this, Greenville and MacAulay (2004) showed that some restriction on effort, through the use of a tax, could yield positive changes in total effort and harvest post the establishment of a protected area.

For homogenous open-access fisheries, Conrad (1999) found two benefits from protected area creation. First, the creation of the protected area could reduce the overall variation in biomass (a hedge benefit); and second, protected areas could be used to reduce the costs of management mistakes. The hedge benefit was found to occur for fairly large protected areas (around 60 per cent of the fishery). Similar results were found by Hannesson (2002), where, with one area closed, the average catch increased, and variation fell. Hannesson (2002) suggested that reduced catch variation was due to the migration effect, with instances where the biomass falls such that it was uneconomic to fish reduced. This result did not hold for a fishery with either very high or very low cost of effort (Hannesson 2002).

The effect of protected areas on harvest and resource rent variability was further explored by Grafton *et al.* (2005a, 2006) and Greenville and MacAulay (2006). Grafton *et al.* (2006) examined protected areas in a fishery characterised by environmental stochasticity and the presence of an uncertain negative shock. The fishery was assumed to be comprised of a single biomass, with a uni-directional flow of biomass between protected area and fishery. Using a dynamic simulation model, Grafton *et al.* (2006) found the establishment of a protected area reduced the effects of negative shocks on the fishery, effectively smoothing harvest and improving resource rent for small sized protected areas (around 20 per cent of the fishery). Grafton *et al.* (2005a) state that whilst the use of a protected area will not guarantee against a population collapse, it can generate economic benefits through the buffer effect of stocks in the protected area.

3. The stochastic bioeconomic model

Bioeconomic models have been used to evaluate the use of marine protected areas as a tool for fisheries management by various authors (Hannesson 1998, 2002; Sumaila 1998; Conrad 1999; Pezzey *et al.* 2000; Sanchirico and Wilen 2000, 2001; Anderson 2002; Greenville and MacAulay 2004, 2006; Grafton *et al.* 2005a, 2006; and many others). The approach used in this study follows the model outlined by Greenville and MacAulay (2006).

The model sets out the exploitation of a fishery comprised of two-species interacting under a predator–prey relationship. The species occur within two subpopulations and migrate between the patches according to relative densities. Two cases of density-driven dependent dispersal are examined: first, when feedback is allowed and dispersal occurs based on differences in relative densities (density-dependent); and second, where there is no feedback and dispersal is by a uni-directional flow (sink-source).

Harvest in the fishery is assumed to follow a Schaefer (1957) production function with a constant per unit cost of effort (c). The Schaefer production function is represented by $h_i^j = q_i^j E_i^j J_i^j$ where h_i^j is the level of harvest of species j in patch i, q_i^j is the catchability coefficient of species j in patch i, E_i^j is the level of effort applied to species j in patch i, and J_i^j is the level of biomass of species j in patch i (Greenville and MacAulay 2006). The equations of motion are given in Equations (1) and (2), with X_i the prey species and Y_i the predator species (Greenville and MacAulay 2006):

$$\dot{X}_i = X_i\left[r\left(1 - \frac{X_i}{K_i}\right) - aY_i\right] + z_i^x - q_i^x E_i^x X_i \tag{1}$$

$$\dot{Y}_i = Y_i\left[s\left(1 - \frac{bY_i}{X_i}\right)\right] + z_i^y - q_i^y E_i^y Y_i \tag{2}$$

where r is the intrinsic growth rate, K_i the carrying capacity of patch i, a and b the predation parameters (a, $b > 0$), z_i^x and z_i^y the dispersal relationships and all other variables as defined. The dispersal patterns are given in Equation (3) for density-dependent with prey species as the example, and Equation (4) for a sink-source flow (source patch) taking predator species as the example (the sink patch has a positive coefficient)

$$z_i^x \equiv g^x\left(\frac{X_j}{K_j} - \frac{X_i}{K_i}\right) \tag{3}$$

$$z_i^y \equiv -g^y\left(\frac{bY_i}{X_i}\right). \tag{4}$$

4. The Manning Bioregion commercial fishing industry

Currently, seven wild-harvest fisheries are commercially fished within the proposed parks' boundaries (Figure 1). Fishery catch and value for six of the fisheries is given in Table 1. In some fisheries, there has been a notable reduction in catch (Fish Trawl and Ocean Prawn trawl fisheries). It is unknown whether the catch declines have been caused by normal seasonal variations in stocks and weather (such as droughts), or result from a decline in the resource base.

The Ocean Trap and Line and Ocean Prawn Trawl fisheries were chosen for the case study as they provide the best examples of fisheries which predominantly harvest predator and prey species, respectively.

5. Model calibration

Data on catch, value and effort were obtained from the NSW Department of Primary Industries, the managing authority. In total, there were 84 monthly observations on catch and effort from July 1997 to June 2004. In the model, the predator and prey species were obtained by aggregating the catch in the fisheries to form a 'representative' species. Whilst this has shortcomings, relating to species interaction effects (assumed to be captured in the overall

Table 1 Fishery catch and value in the Manning Bioregion

Year		1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04
Estuary General	Catch (kg in '000s)	725	878	752	746	956	753	543
	Value ($ in '000s)	2340	2494	2636	2702	3513	3473	2261
Fish Trawl	Catch (kg in '000s)	569	515	314	248	234	268	193
	Value ($ in '000s)	1683	1574	1017	848	806	936	613
Ocean Hauling	Catch (kg in '000s)	643	398	501	361	542	596	513
	Value ($ in '000s)	1146	739	1013	738	1169	1329	1036
Ocean Prawn Trawl	Catch (kg in '000s)	335	306	209	248	207	193	120
	Value ($ in '000s)	2751	2552	2199	2368	1755	1935	1459
Ocean Trap and Line	Catch (kg in '000s)	238	266	218	147	147	126	130
	Value ($ in '000s)	968	1089	962	749	760	621	634

Source: Unpublished data from DPI catch records.

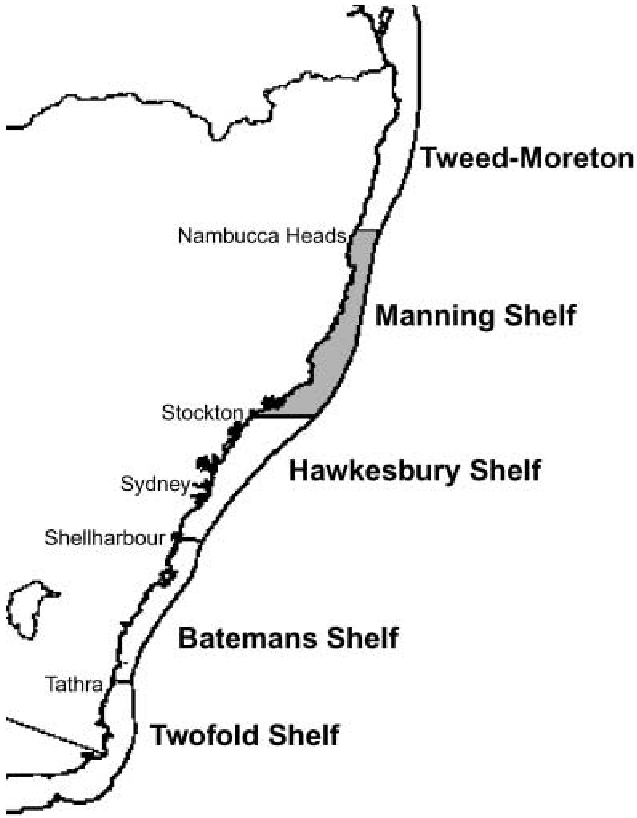

Figure 1 Bioregions in New South Wales, Australia.

yield effort relationship), other methods of aggregation have equally restrictive assumptions and can lead to spurious regressions (see Halls *et al*. 2006). The most common species caught in the predator fishery include Trevally, Bonito, Morwong and Snapper, with prawns, School Whiting and Baby Octopus accounting for the majority of prey catch.

Catch per unit effort was used as proxy for biomass as it provides an indication of the productivity of the biomass (Kirkley *et al*. 2002). Catch per unit effort, however, does not directly measure biomass (Felthoven *et al*. 2004). It is acknowledged that catch per unit of effort has many shortcomings (see Richards and Schnute 1986) and can potentially introduce endogenity into regressions. Due to limited data, however, an alternative was not available, so the results are conditional on the use of this measure. Changes in catch per unit effort for the two fisheries are shown in Figure 2.

Some dynamics of the stocks can be derived from examining changes in harvests in response to the other variables in the model. A lag of four periods was chosen for the predator–prey interaction as for lags of shorter or longer length there was no discernable relationship.

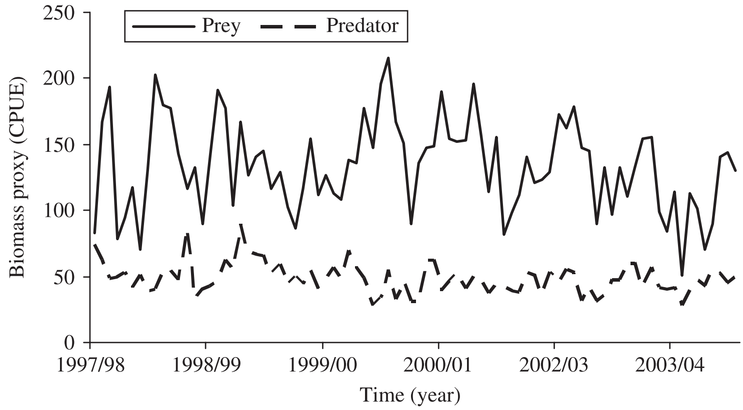

Figure 2 Prey and predator catch per unit effort.

In order to find estimates of the parameters in the bioeconomic model the fishery was assumed to be in a steady-state. Changes in catch per unit effort are relatively constant overtime, providing some (albeit limited) evidence that the fisheries are in steady-state. However, given the limited dataset, we have made the assumption that the fishery was in steady-state, and that it will shift to another steady-state following a change in effort or regulation of the fishery. Due to this restrictive assumption, key sensitivities have been identified in the analysis. The relationship between catch and growth (assumed to equal harvest) at a fishery level can be defined and is given by Equations (5) and (6):

$$h(X) = rX - \frac{rX^2}{K} - aXY \tag{5}$$

$$h(Y) = sY - \frac{sbY^2}{X} \tag{6}$$

where $h(X)$ and $h(Y)$ are harvest of prey and predator species, respectively. The linear reductions of Equations (5) and (6), augmented by a constant term (c_x and c_y, respectively) are given by Equations (7) and (8), respectively. The constant terms were added to the regressions to avoid bias in the estimations as without a constant term, the estimates would be biased towards zero. Despite the use of the constant term, estimated values of these terms were found to be small and insignificant. The removal of the constant term does not lead to any significant change in the estimates. Coefficients $\acute{a}$, $\hat{a}$, $\ddot{a}$, $\ddot{o}$, $\ddot{e}$ and $\tilde{a}$ are to be estimated, with $\mathring{a}_t^x$ and $\mathring{a}_t^y$ representing error terms assumed to be independent and identically normally distributed for prey and predator species, respectively. The W_{t-1} term is used to represent weather effects on the prey biomass, and is represented by the monthly rainfall recorded at Nelson Bay located at the centre of much of the fishing activity in the region. Weather is believed to influence the level of biomass for prawn species through its influence on fresh water and nutrient flow into estuaries

Table 2 Parameter estimates

Coefficient	Estimate	*t*-ratio	Corrected estimate	*t*-ratio	Parameter	Estimate	Corrected estimate
Prey							
α	0.697	3.456***	0.416	3.010***	r	0.697	0.416
β	−0.015	−1.977***	−0.007	−1.366	K	47.599	58.830
δ	−0.011	−2.429 ***	−0.006	−1.581*	a	0.011	0.006
φ	0.004	3.626***	0.003	3.861***	φ	0.004	0.003
Predator							
λ	0.518	8.102***	NA	–	s	0.518	NA
γ	−0.053	−0.766	NA	–	b	0.102	NA

*** Significant at 5%, ** Significant at 5% and * Significant at 15%; adjusted R^2 predator = 0.6861; adjusted R^2 corrected prey = 0.7251.

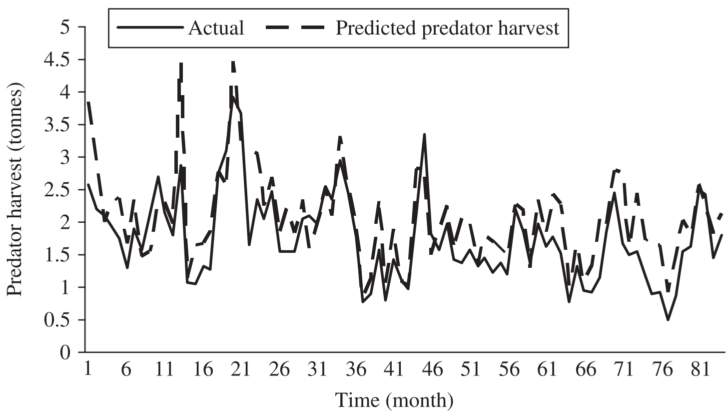

Figure 3 Actual vs predicted predator harvests.

$$h(X_t) = c_x + \alpha X_t - \beta X_t^2 - \delta XY_{t-4} + \varphi W_{t-1} + \varepsilon_t^x \tag{7}$$

$$h(Y_t) = c_y + \lambda Y_t - \gamma \frac{Y_t^2}{X_t} + \varepsilon_t^y. \tag{8}$$

The parameter values for b and K (in Equations (5) and (6)) cannot be directly estimated. An estimate of K can be obtained from *á/â* following Equation (5) and represents the point where growth is equal to zero (biomass equal to either zero or K). Similarly, an estimate of b is obtained from *ã/ë* following Equation (6) (Table 2).

Durbin–Watson tests for autocorrelation in the predator model were not conclusive. Dicky–Fuller tests for unit roots were conducted on the variables, with results being not inconsistent with the data having a stationary mean. A plot of the actual and fitted predator harvests is given in Figure 3.

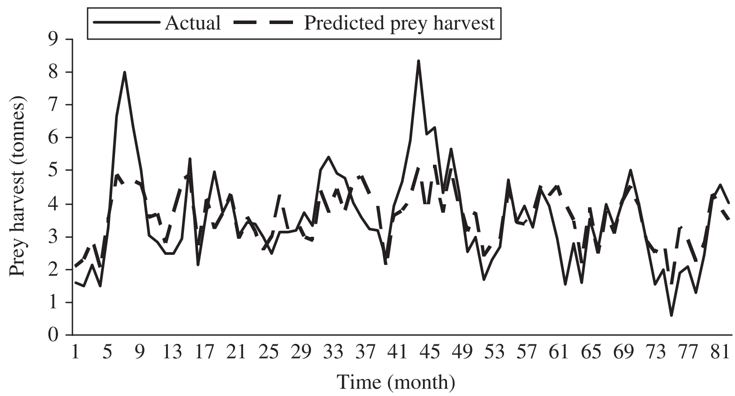

Figure 4 Actual vs predicted prey harvests.

The estimate of the *b* parameter for the predator model was found to be less than one. This result means that in this system there is a potential for predator numbers to exceed prey numbers as the carrying capacity of predators based on prey numbers exceeds the total number of prey. This result is believed to be due to the fact that the predator species do not exclusively feed on the species in the Ocean Prawn Trawl Fishery. As predators are likely to eat other species within the marine environment, there is a potential misspecification problem. However, given the available dataset this could not be tested. There is an implicit assumption that once a marine protected area is established, other food sources also increase within the protected areas boundaries and provide additional carrying capacity for the predator population levels.

For the prey model, all parameter values had the expected signs. A Durbin–Watson test confirmed first-order autocorrelation. A unit-root test was conducted with the results not inconsistent with the data having a stationary mean. Estimates for the parameters corrected for autocorrelation (via the Cochrane–Orcutt procedure) are reported as the 'Corrected Estimates' in Table 2. A plot of the actual and fitted prey harvests is given in Figure 4.

From the estimation, distributions for the growth rates, weather and the correlation between the species were obtained. The distributions for *r*, *s* and *W* are given in Figure 5a–c, respectively. The distribution for the weather term is derived from monthly observations of rainfall at Nelson Bay from January 1882 to March 2005.

The correlation between the growth rates was taken from the correlation between the two error terms from the estimated regressions. The correlation was found to be equal to 0.53. Prices received for the two-species were taken as the average unit value of catch over the period from July 1997 to June 2004 (prey \$8/kg, predator \$4.75/kg). Information on the cost of effort is not known, and was estimated by calibration: solving for the level of cost that

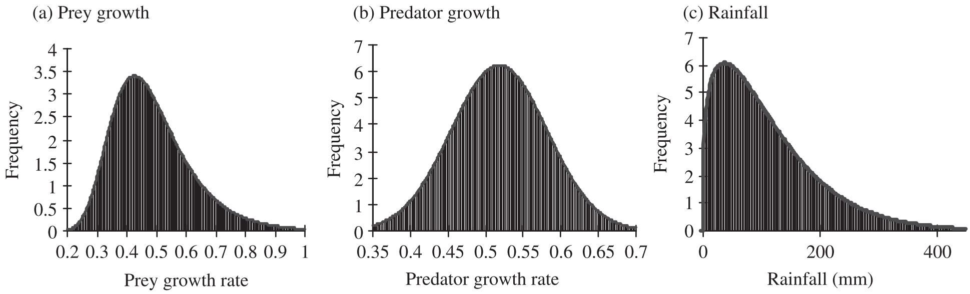

Figure 5 Distributions of stochastic parameters. (a) Extreme value, mean: 0.43, SD: 0.14; (b) normal, mean: 0.52, SD: 0.06; (c) Weibull, mean: 112, SD: 88.

gave rise to the current harvests given other parameter estimates. The cost figures need to take into account resource rent. As input controls are used, it is likely that some rent, although marginal, may be generated in the fishery. Further, this rent has the potential to continue as management controls are improved over time to maintain current harvests and limit fishers from substituting uncontrolled for controlled inputs.

A state-wide economic survey of commercial fishers in 1999–2000 was commissioned by the NSW Department of Primary Industries. This cost and revenue data (NSW Department of Primary Industries 2004) were used to estimate the potential rent in the fisheries (by calculating the economic profit earned, on average, by fishers). It was estimated that levels of resource rent generated in the Ocean Prawn Trawl Fishery were equal to 8 per cent of total costs. For the Ocean Trap and Line Fishery, the environmental impact statement is yet to be released, so the rent generated was assumed to be the same as for the Ocean Prawn Trawl Fishery. Average cost estimates were found to be \$133 and \$69/day for the Ocean Prawn Trawl, and Ocean Trap and Line fisheries, respectively (average cost differences consistent with fishing methods used in each fishery).

6. Simulation results

The spatial structure of the stocks and dispersal patterns are unknown. As a consequence, several alternate scenarios were examined in the simulations. In the first, growth was assumed to be homogenous across the patches (Scenario 1). Under the second scenario, the protected area was assumed to be created in areas of greater biological value (Scenario 2). The potential surplus yield in these grounds is greater than that experienced in the open fishing ground per unit of carrying capacity.

Protected areas were modelled by preventing fishing occurring in a patch equal to the size of the percentage area closed (given scenario assumptions). For all scenarios, density-dependent and sink-source dispersal relationships were examined with varying levels of migration. As no data on species migration were available, various levels of dispersal were explored to examine the sensitivity of the results to this parameter (g). In addition to this, changes in the current management arrangements were examined (Scenario 3).

For Scenarios 1 and 2, a simulation approach was taken to explore the effects of protected area creation. For Scenario 3, the model was optimised first to determine optimal levels of biomass. Then, the effect of protected area creation was explored via a simulation approach as done for the first two scenarios, but with optimal biomass maintained in fishing ground.

In the following sections, results for net social cost of protected areas are presented in the various figures. Results for other variables are described but not presented in figures.

6.1 Scenario 1: homogenous growth

The results for Scenario 1 are presented in this section for density-dependent and sink-source dispersal. In general, a small-sized marine protected area of around 15–20 per cent of the fishery increased resource rent.

6.1.1 Density-dependent dispersal

Changes in mean resource rent from the establishment of protected areas are sensitive to the level of dispersal that occurs. The greater the migration away from the reserve, the greater are the potential benefits from protected area establishment. The establishment of a protected area had different effects on the predator and prey species. Total mean prey numbers fall for small to medium sized protected areas, as a result of increased predator numbers leading to an overall reduction in mean prey harvests (both overall and in the patch where fishing is permitted). This effect can be seen as 'restoring the balance' in population numbers. As predator numbers are relatively low, compared with no-harvest levels, the increase in predator numbers is significant with a protected area, increasing total mean harvests and effort for this species. Also, as the predator effect in this scenario dominated the outcome, total effort (predator and prey combined) increased for all dispersal values.

The net social cost, in terms of forgone resource rent, is depicted in Figure 6 for both fisheries. For all dispersal levels, there is a diminishing cost of additional increases in protected area size. From Figure 6, for $g = 3$, a protected area of 15 per cent of the total fishery increased mean resource rent. The optimal protected-area size increases to 20 per cent when $g = 4$. For lower levels of dispersal ($g = 2$), however, protected areas did not increase mean resource rent.

The variation over time of mean resource rent and harvest decreased with increased size of protected area under all levels of migration. This 'hedge' effect; however, for any sized protected area was lessened with increased dispersal, because with increased dispersal the reliance of harvests on dispersal also increases. As dispersal is analogous to an excess supply (determined by

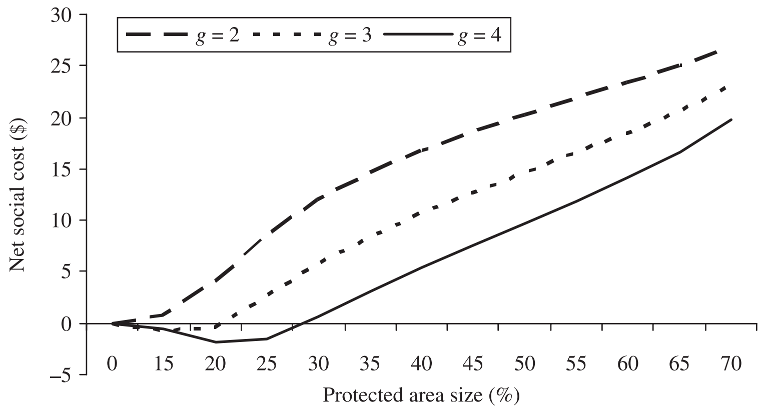

Figure 6 Net social cost of establishing a marine protected area with density-dependent dispersal.

within-patch interactions), it is more variable than harvesting the underlying resource itself, making total harvests more variable. This was seen for predators but not for prey. Mean fishing-ground harvest variation increased for prey and decreased for predators.

6.1.2 Sink-source dispersal

Under sink-source dispersal, the ability of the protected area to yield a net benefit was less than seen for density-dependent dispersal. For $g = 2$, the protected area did not yield any benefits in terms of resource rent. The creation of small to medium protected areas reduced the mean steady-state prey biomass. Given this, mean steady-state prey harvest fell for the fishery overall and in the remaining fishing ground. Mean steady-state predator biomass and harvests increased post-protected area creation. Again, these results were due to the low levels of exploited predator biomass which increased significantly post-protected area creation.

The net social cost in terms of forgone resource rent from protected area establishment is given in Figure 7. Protected areas decreased total resource rent except when there was high dispersal ($g = 4$) and a minimum-sized protected area (25 per cent of the fishery). For lower dispersal rates, there was no size of protected area that yielded an increase in resource rent.

The higher costs from smaller protected areas under sink-source dispersal occurred because of the difference in the dispersal drivers. As there was a large difference between the population densities before and after creation of the protected area, density-dependent dispersal induced a greater flow of biomass from the protected area (as it is driven by differences in relative densities) than that seen with sink-source dispersal (where differences in patch population densities do not increase migration).

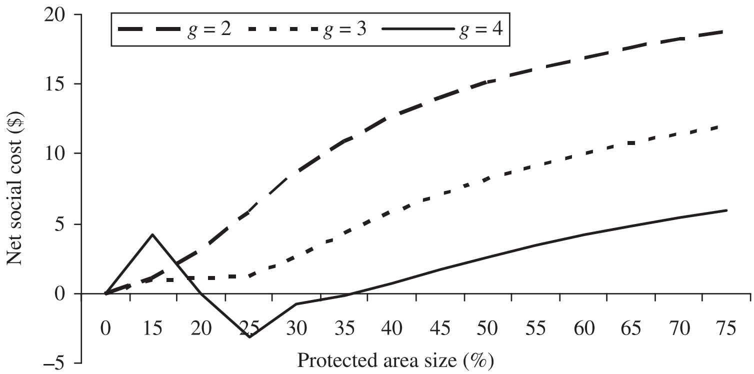

Figure 7 Net social cost of establishing a marine protected area with sink-source dispersal.

After the establishment of the protected area, mean effort levels in the predator fishery increased. For the prey fishery, however, total effort levels fell. Overall the increase in predator numbers and thus effort dominated, with total mean effort levels increasing. This result was seen for all sized protected areas with the exception of protected areas of 15 per cent for with dispersal levels ($g = 2$).

Variation in the mean steady-state total rent from the fisheries also increased for small-sized protected areas and high dispersal. When $g = 4$, the increase in mean steady-state rent was accompanied by an increase in variation. For larger-sized protected areas, variation in resource rents decreased, producing a hedge against normal fishery variation.

6.2 Scenario 2: heterogenous growth

With heterogenous growth, the area chosen to be protected was assumed to be of higher biological productivity than the surrounding fishing ground. Growth rates in the protected area were assumed to be a factor of 1.25 greater than those estimated, with growth rates in the fishing grounds assumed to be adjusted by a factor of 0.75. The choice of these factors was arbitrary.

As with the homogenous biomass scenario, suboptimal biomass levels were simulated.

6.2.1 Density-dependent dispersal

Under density-dependent dispersal, and given low dispersal rates ($g = 2$), the creation of a protected area in the fishery always decreased the mean resource rent generated in the fishery. At higher dispersal rates, small sized protected areas generated a small net gain to the fishery. As before, the main effect of protected area creation was seen for the predator species. Small sized protected areas increased mean predator numbers and decreased mean prey

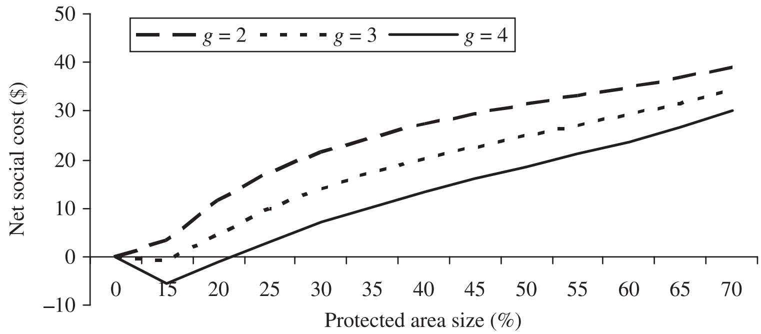

Figure 8 Net social cost of establishing a marine protected area with density-dependent dispersal scenario 2.

numbers, as without fishing pressures, the population ratio changed. The increased movement of mean predator numbers also drove the changes in the level of resource rent. Results for the surrounding fishing ground were similar to those under homogenous growth.

Changes in effort levels differed for each of the fisheries. Effort levels in the fishery targeting predator species increased while, for the prey fishery, effort levels fell. Overall, for certain dispersal levels ($g = 2$ and 3), the increase in effort in the predator fishery exceeded the fall in effort in the prey fishery.

Under this scenario the opportunity cost curves shifted to the left (Figure 8). For higher dispersal rates ($g = 3$ and 4), the optimal protected area size was smaller than for Scenario 1 (Figure 6).

Also, the ability for protected areas to hedge against variation in populations and resource rent was lessened by protecting areas with higher intrinsic biomass growth. For prey species, protected areas of only very small size (up to 15 per cent of the fishery) decreased the variation in mean prey numbers. Larger protected areas increased the variation in predator numbers.

6.2.2 Sink-source dispersal

Under sink-source dispersal, total mean resource rent in the fishery fell for all sized protected areas (Figure 9). This fall occurred as the flow of stocks from the protected area to the fishing grounds was less than under density-dependent dispersal due to the differences in the dispersal drives. This meant that the forgone catch that previously occurred within the protected area was not sufficiently compensated by the dispersal that occurred in post-protected area creation.

The remaining results were similar to the other scenarios with the exception of mean prey harvest and effort levels in the surrounding fishing ground. As dispersal levels increased, the increased flow for predators from the protected area increased predation in the fishing ground, decreasing prey harvest and effort. The increased predator numbers, however, increased mean effort

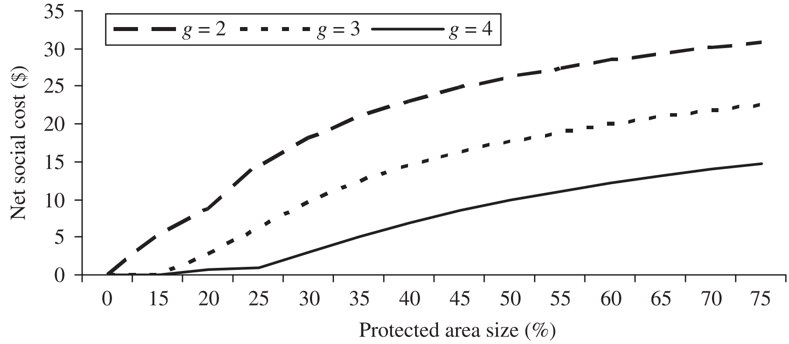

Figure 9 Net social cost of establishing a marine protected area with sink-source dispersal scenario 2.

and harvest for this species for small sized protected areas, which with high dispersal rate ($g = 4$) was sufficient to increase total mean effort (prey and predator combined) post-protected area establishment.

In contrast to density-dependent dispersal, the ability of protected areas to reduce the variation in mean resource rent and prey biomass was enhanced by protecting areas higher intrinsic species growth. Protected area creation of all sizes lessened the variation in mean resource rent levels. Further, small sized protected areas decreased variation in mean prey and predator numbers and prey harvests in the surrounding fishing grounds.

6.3 Scenario 3: improved institutional arrangements

Optimal biomass levels for prey and predator species were determined using the optimal biomass relationship derived by Greenville and MacAulay (2006). The optimal biomass in each patch is found using:

$$\delta = \frac{c_i^j w_i^{j'}(F_i^j(\cdot) + z_i^j)}{w_i^j(p_i^j q_i^j w_i^j - c_i^j)} + (F_i^{j'}(\cdot) + z_i^{j'}) \tag{9}$$

where w_i^j is the biomass of species j in patch $i = (w_i^j = J_i^j + z_i^j)$, $F_i^j(\cdot)$ is the growth function of species j in patch i, $\ddot{a}$ the social discount rate, $w_i^{j'}$, $z_i^{j'}$ and $F_i^{j'}(\cdot)$ are the first derivates of w_i^j, z_i^j and $F_i^j(\cdot)$ with respect to biomass J_i^j, with all other variable as defined.

When solving for optimal biomass levels, an interesting result was observed. Given the estimated parameters, it was optimal to prevent fishing on small subpopulations of prey stocks as a greater return can be obtained from the resulting increased migration and thus catch. As predator stocks can exceed prey stocks (as the estimated carrying capacity parameter of predators (b) was less than 1), protecting prey stocks in smaller patches

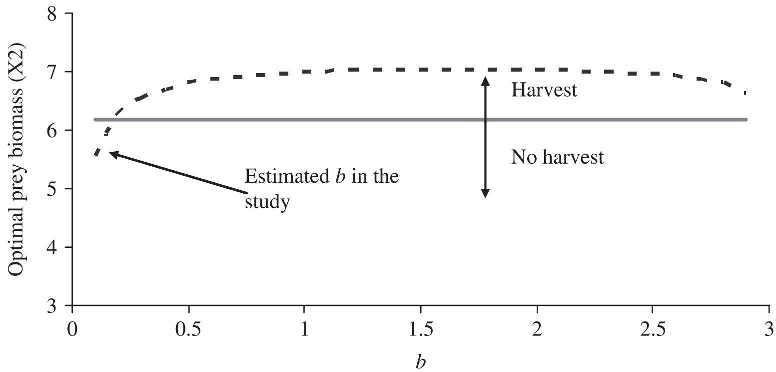

Figure 10 Optimal prey stock as a function of the predator biomass carrying capacity parameter under sink-source dispersal (source patch size 20 per cent of fishery).

allows them to be 'transformed' into greater predator numbers. The optimal biomass is depicted in Figure 10 as a function of the parameter *b* with the solid horizontal line representing the constraint that effort must be greater or equal to zero (biomass above this line represents points of harvest, below, points of no harvest). For value of *b* less than 0.18, it is optimal not to fish the prey biomass in the small patch (in this case the source patch).

For values of *b* that lead to unconstrained optimal biomass levels (those determined without the effort constraint in the optimisation) below the harvest/no harvest line, maintaining a fishing pressure on this stock reduces resource rent. Thus, for certain values of *b*, it is optimal to protect the prey stock, meaning that for a single species, a marine protected area is optimal in the absence of other factors (such as uncertainty) when consideration is given to that species' links with other harvestable species.

6.3.1 Density-dependent dispersal

Given optimal biomass levels and homogenous growth rates, it was found that no harvest on prey was optimal for patches of 15–20 per cent of the fishery. Thus, the initial no protected area case represents this.

The creation of a protected area with optimal management and density-dependent dispersal shifted the opportunity cost curves up and to the left compared to those under suboptimal management. Thus, no size of protected area was found to be optimal for *both* stocks (Figure 11). However, this does not imply that the use of a protected area is non-optimal. On the contrary, for optimal management to occur, protection of prey stocks in small patches of the fishery was required. From this result, multiuse zones where certain fishing activities are prohibited will be optimal.

Overall, total mean effort (combined prey and predator effort levels) increased for small and medium sized protected areas. As under the first two scenarios, this was driven by an increase in predator numbers after protected area creation.

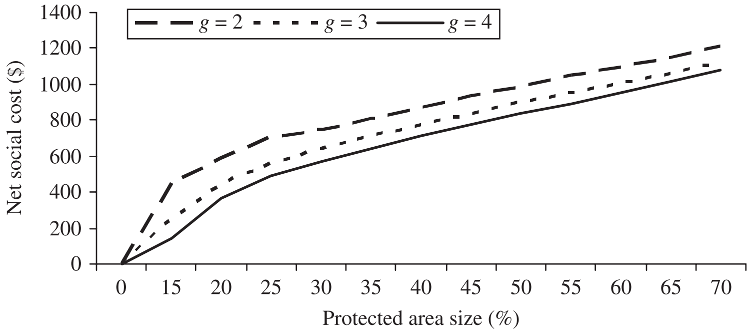

Figure 11 Net social cost of establishing a marine protected area with density-dependent dispersal scenario 3.

In terms of variation, protected areas with small levels of dispersal ($g = 2$) increased the variation of mean resource rent and stocks. For larger dispersal levels ($g = 4$), mean resource rent and harvest variation decreased with protected area creation, with larger protected areas having the greatest effect.

6.3.2 Sink-source dispersal

Under sink-source dispersal, protected area creation decreased total mean resource rent for all sized protected areas. Again, this result needs to be considered in the context of prey stocks being protected for small-sized patches. Mean prey numbers increased for small-sized protected areas. Despite increases in mean predator harvests in the fishing ground, the increase was not great enough to lead to an overall increase in the mean effort in the predator fishery. For the prey fishery and overall, total mean effort levels fell. Small-sized protected areas had a lower opportunity cost than that seen for density-dependent dispersal (Figure 12).

Results obtained for variation were similar to those under the other scenarios. However, for smaller sized protected areas, mean resource rent variation increased with medium and high dispersal levels ($g = 2$ and 3). Variation in total mean predator harvests also fell for most sized protected areas which were not seen under suboptimal management. For high dispersal levels, all harvests and rents became more variable than under suboptimal management due to the greater dependence of harvests on dispersal.

6.4 Summary of results

A summary of the results presented previously is presented in Table 3.

7. Discussion

Under the both homogenous and heterogenous growth rates, it was found that protected areas have a greater potential to reduce total resource rent

Table 3 Summary of results

Outcome	Density-dependent	Sink-source
Scenario 1		
Mean resource rent	Increased for small sized protected areas with $g = 3$ or 4	Decreased for all expect $g = 4$ and protected area 25% of fishery
Variation of mean rent	Decreased for all protected area sizes and dispersal levels. Decreases less for higher dispersal levels	Increased for small sized protected areas but fell for medium to large sized protected areas under all dispersal levels
Mean harvest/effort	Increased in the predator fishery, decreased in the prey fishery	Increased in the predator fishery, decreased in the prey fishery
Variation harvest/effort	Decreased for all protected area sizes and dispersal levels. Decreases less for higher dispersal levels	Increased for small sized protected areas but fell for medium to large sized protected areas under all dispersal levels
Scenario 2		
Mean resource rent	Increased for small sized protected areas with medium to high dispersal levels ($g = 3$ or 4)	Decreased for all sized protected areas and dispersal levels
Variation of mean rent	Decreased for all sized protected areas and dispersal levels	Decreased for all sized protected areas and dispersal levels
Mean harvest/effort	Increased in the predator fishery, decreased in the prey fishery	Increased in the predator fishery, decreased in the prey fishery
Variation harvest/effort	Decreased for small sized protected areas with low dispersal ($g = 2$), but increased for larger protected areas and dispersal levels	Decreased for all sized protected areas with low dispersal, but increased with high dispersal ($g = 4$)
Scenario 3		
Mean resource rent	Decreased for all sized protected areas and dispersal levels	Decreased for all sized protected areas and dispersal levels
Variation of mean rent	Increased for small sized protected areas with low dispersal, decreased for larger protected areas and dispersal levels	Increased for small sized protected areas with high dispersal, decreased for larger protected areas with all dispersal levels
Mean harvest/effort	Decreased for all sized protected areas and dispersal levels	Decreased for all sized protected areas and dispersal levels
Variation harvest/effort	Increased for small sized protected areas with low dispersal, decreased for larger protected areas and dispersal levels	Increased for small sized protected areas with low dispersal, decreased for larger protected areas and dispersal levels

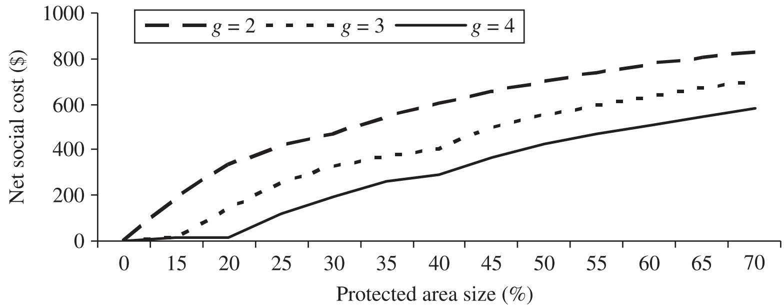

Figure 12 Net social cost of establishing a marine protected area with sink-source dispersal scenario 3.

within the Manning Bioregion than to increase it. Losses were found to be more common with only small gains estimated for a limited number of cases. Also, outcomes from protected area creation were dependent on some level of management of the fishery. Without some form of management, no structure exists to capture the benefits from improved resource use, and therefore, protected areas should be viewed as a complement to current management arrangements and not a replacement. For reserves to be successful in fisheries management, they need to be integrated with current arrangements and monitored to ensure continued success (Grafton *et al.* 2005b).

Despite the limited chance for protected areas to increase resource rent, the results presented provide an indication as to the possible effects of a protected area in this fishery. Both the nature and extent of the dispersal from the protected area are key features in determining the economic outcome from creation (these effects were common across the different scenarios). The greater the level of dispersal, the greater the benefits as more of the biomass that occurs within the protected area is likely to flow to the surrounding fishery. As large differences in relative densities occur irrespective of the size, the value of small-sized protected areas is enhanced through density-dependent dispersal. Under sink-source dispersal, differences in relative densities do not encourage increased flows from the protected areas, making the level of dispersal more dependent on protected area size.

If areas of higher quality are protected (heterogenous patches), the potential for protected areas to improve resource rents are more limited. Despite this, for medium to high dispersal patterns, small sized protected areas can improve resource rents under density-dependent dispersal. In conjunction with this, these protected areas have the potential to lower variability in harvests and rents.

The creation of a marine protected area in the Manning Bioregion is likely to have different distributional effects on the two fisheries examined. For the prey fishery, the benefits of protected area creation are limited by the effects of predation. The protected area is less likely to increase mean harvests and fishery rent post establishment. Further, certain sized protected areas increased the variability of mean harvests, meaning that overall harvests were not only reduced but more variable. The counter situation occurred for the predator fishery, which is more likely to benefit from protected area creation. Increased mean predator numbers increased mean predator harvests. Despite the potential gain, in the open fishing grounds harvests of predator species are likely to become more variable.

The distributional effects were seen through changes in pre and post effort levels. Under most scenarios and dispersal patterns, total effort in the fishery increased. This was due to the increase in effort applied to predator species. The distributional effects are likely to lead to opposition from certain fishers despite the potential Pareto improvement. Grafton and Kompas (2005) suggest a way to manage these concerns is to establish protected areas of smaller than optimal size in different locations to both simultaneously improve ecology and economic outcomes. Compensation schemes can be used for lost access rights, and can be viewed as a re-distribution of the potential benefits. In setting up such compensation schemes, managers should be mindful of the overall costs and benefits, including the monitoring and enforcement costs of protected area establishment.

The greater effort levels in the surrounding fishery may offset the conservation outcome achieved by the protected area. If further environmental damage is created through this shift, then those costs would need to be considered against the benefits that would accrue to the fishery. However, the shift represents a movement in fishing practice away from trawling methods (often deemed destructive) to less destructive trap and line methods.

For the two fisheries as a whole, the creation of certain sized protected areas can yield a hedge against variation in overall harvests and resource rent. For this to occur, a minimum sized protected area is required. Medium to large sized protected areas were found to be more likely to lead to a decrease in normal variations in biomass (and thus harvests and resource rent). Smaller sized protected areas do not increase biomass greatly above exploited levels, limiting the ability for biomass in the protected area to reduce normal fluctuations in populations caused through environmental stochasticity.

For small patches, given the parameter estimates, it was found that it was optimal to protect prey biomass. The return from harvesting the extra predator biomass generated from the patch was greater than return from harvesting the underlying prey stock. It is better to 'value add' the prey stock by allowing them to be consumed by the predator stocks. Key determinants of this result are the predator stock carrying capacity parameter (b) which determines, in part, the growth rate of predators (given logistic growth), and the carrying capacity of the prey stock (K_i).

An implication to be derived from this result is the potential to use multiuse protected area zones. Given certain characteristics of the stock and the fishery, multiuse zones that prohibit the taking of a certain species can be used as a tool to achieve the optimal management of fishery resources. Multiuse zones have become a common element in many marine protected areas, and are advantageous on both political grounds (through reduced opposition), and on economic grounds (as they can be used to maximise the value of the resource).

8. Concluding comments

Whilst protected areas have the potential to become a useful tool for the management of fisheries, for the Manning Bioregion, however, it is unlikely that a protected area will increase resource rent. The results from the analysis suggest that, if they were implemented, protected areas would have differing effects on fisheries that target different species, with a protected area potentially adversely affecting prey fishers, but benefiting predator fishers. For the Manning Bioregion, two fisheries were examined separately, so the full effect on all the fisheries that operate in that region is unknown.

Results from the model suggest that benefits in the form of improved resource rent and reduced harvest variation are possible, albeit unlikely. These results are, however, conditional on the maintenance of current resource rent levels in the fishery. As input controls are exclusively used in the fishery, there is a strong possibility that any resource rent will be lost due to competitive behaviour resulting in increased investment, and consequently increased cost, in the fishery. Given this, it is important for fishery managers to ensure the current mix of controls are not only achieving sustainable harvest levels, but are maximising the resource rent generated in the fishery.

Under optimal steady-state management of fishery resources, the protection of both species is non-optimal. Rather, the optimal strategy is protection of prey species in small patches. The use of multiuse zones within a protected area which allow for the protection of prey species but allow the taking of predator species would improve the level of resource rent generated in the fishery.

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