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Protected areas in fisheries: a two-patch, two-species model*

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The use of marine protected areas as a fishery management tool has been suggested as a hedge against management failures and variation in harvests. A stochastic bioeconomic model of a hypothetical predator–prey fishery is used to test the performance of protected areas in a fishery with heterogenous environments. Protected areas are analysed under density-dependent and sink-source dispersal relationships between the subpopulations that occur within the fishery. Differing management structures governing resource extraction are analysed. The focus of the study is placed on the biological and management characteristics that yield benefits to both fishers and society. It is shown that the establishment of a protected area improves fishery rent and lowers harvest variation. This result is sensitive to both current management controls and the correlation between species and patches.

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

1. Introduction

In recent years, the area of marine environments protected from commercial fishing pressure has increased. Marine protected areas have been advocated in areas where other forms of fishery management are impractical or unsuccessful (Sumaila 1998). Arguments for protected area use are based around the heterogeneous nature of fisheries, uncertainties in marine populations, and as a hedge strategy to reduce risks of overexploitation (Conrad 1999). Through the protection of biodiversity and improving the resilience of the ecosystem, protected areas may mitigate the effects of negative shocks and act as a hedge against uncertain shocks (Ludwig *et al.* 1993; Botsford *et al.* 1997; Grafton *et al.* 2004a).

The purpose of this paper is to examine the effects of marine protected area establishment in a discrete environment (i.e., a fishery of subpopulations located in different patches). As the population in each of the patches does not directly create a greater homogenous population, the effects from the protected area, particularly on the variability of effort and harvest within the

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fishery, are believed to differ from results found in previous studies. A predator–prey model is chosen for the analysis as species interactions are likely to have a significant effect on the outcomes. In some instances, it is considered that the creation of a protected area will not yield any benefit to wild harvest fisheries due to likely increases in predator numbers, thus reducing or eliminating the flow of biomass to the surrounding fishing grounds. By including predator–prey dynamics, these issues are explicitly included in the analysis.

The effect of the predator–prey interaction in a stochastic metapopulation fishery where both species are harvested has not been examined. In a deterministic model by Greenville and Macaulay (2004) and a stochastic model by Grafton *et al.* (2004a), the establishment of a marine protected area was seen to yield a positive effect on harvest given some pre-existing managerial controls. In a stochastic environment, the flow of biomass from one patch to the other will not be stable, and can be seen as analogous to an excess supply in a world trade environment. Excess supply is a residual difference dependent on both demand and supply within a domestic economy, and as such, becomes more variable as both demand and supply movements influence its level. In subpopulations, the demand and supply from the patch is dependent on the growth rates from both predators and prey; thus this flow will be more variable than harvest from the patch itself.

The remainder of this paper is organised as follows. In Section 2, a brief overview of the bioeconomic modelling of marine protected areas is given. In Section 3, the bioeconomic model used is presented, with results in Section 4. A discussion of the results and policy implications is presented in Section 5 with concluding comments in Section 6.

2. Bioeconomic modelling of fisheries

Bioeconomic models have been used to evaluate the impact of marine protected areas on fisheries by a number of authors (Hannesson 1998, 2002; Sumaila 1998; Conrad 1999; Pezzey *et al.* 2000; Sanchirico and Wilen 2001; Anderson 2002; Grafton *et al.* 2004a; Greenville and Macaulay 2004, and many others). Many of these models have used undifferentiated biomass to show that marine protected areas have the potential to improve harvests in surrounding fishing grounds and reduce their variation. However, in some instances, these models have ignored characteristics such as heterogenous environments, species interaction, and the current mix of management controls, and therefore have the potential to signal an unrealistic result.

Sanchirico and Wilen (2001) used a metapopulation analysis with different spatial environments described as patches, containing subpopulations of a single biomass. Metapopulation analysis is useful in the study of marine protected areas as the protected area and fishing grounds can be viewed as separate patches. Analogous to separate population patches is the concept of separate age groups (Klieve and Macaulay 1993; Brown and Roughgarden 1997; Bulte and van Kooten 1999).

Under open-access conditions, no increases in economic rent are available with authors using changes in the level of harvest as a proxy for the gain to the fishing industry (Sanchirico and Wilen 2000, 2001). Sanchirico and Wilen (2001) showed that if a pre-reserve harvest equilibrium existed, under certain conditions the establishment of a marine protected area would yield a win–win outcome. Despite this, Hannesson (2002) suggested that the concentration of effort in the remaining area would offset any conservation outcome achieved by the reserve. Sanchirico (2005) analysed a hypothetical fishery consisting of nine patches. They found that the closure of multiple patches reduced net rent and harvest by a smaller amount than the closure of one patch on its own (although it was optimal to have all patches open to fishing). In a multipatch fishery, designating multiple patches to protection would result in a smaller cost for the fishery.

Given limited entry conditions, Sanchirico and Wilen (2001) suggest the establishment of a protected area would require policy-makers to reduce overall effort in the fishery for any restriction beyond open access. Despite this, Greenville and Macaulay (2004) showed that with restrictions on effort, protected areas could yield positive changes in the total effort and harvest post-establishment. Further, given a predator–prey fishery, the authors suggest that protected area outcomes are benefited through stricter controls on prey stocks. Given harvests of only predator stocks, the fishery is effectively reduced to that of a single-species biomass. Grafton *et al.* (2004a) found that, because of the ability of the protected area to hedge against uncertain events, an improvement in fishery rent post-establishment resulted even with optimal management.

Conrad (1999) observed two benefits from a marine protected area. First, the protected area could reduce the overall variation in biomass and harvest (also in Pezzey *et al.* 2000 and Hannesson 2002), and second, it may reduce the costs of management mistakes. Conrad (1999) found that both uncorrelated and perfectly correlated growth reduced the variation in harvest and biomass as low growth rates in one area could be offset by high rates in the other. Hannesson (2002) suggested that the reduced variation in catch was due primarily to the migration effect. With migration after an area has closed, the instances when the biomass fell such that it is un-economic to fish were reduced, with the reverse having a lesser effect.

Marine protected areas have been suggested as a tool to help manage uncertainty and environmental stochasticity while simultaneously generating benefits for both fishers and the environment (Grafton and Kompas 2005; Grafton *et al.* 2005). To mitigate variability in production, the use of protected areas has been suggested as it allows for the protection of both individual species and ecosystem processes. This protection has the potential to improve fishery returns even when stocks are not overly exploited, with the benefits accruing from small-sized protected areas (Grafton *et al.* 2005).

As ecological interactions within fisheries are complex and diverse, the modelling of a single species may exclude results that are important for fisheries management. Many of the fish species commercially targeted are predators, with their management important in determining outcomes from prey species. In a fishery where both predator and prey species are targeted, prey controls can have a significant positive effect on predator species harvests (Flaaten 1998; Greenville and Macaulay 2004). Supriatna and Possingham (1999) suggested a 'rule of thumb' that could be applied for optimal harvesting of predator–prey biomass, such that harvest of 'source' prey populations be more conservative than 'sink' populations, and that predator populations interacting with the 'source' prey populations be harvested relatively more intensely.

Habitat characteristics will play an important role in determining the optimal harvest policy. Neubert (2003) suggests that uniform harvest policies will only be optimal for relatively sedentary species with high population growth rates living in large habitats. For species with low growth rates or high dispersal, species that live in spatially restricted habitats, or those that are easy to catch, a protected area could be used to maximise the value from exploiting these species.

3. The bioeconomic model

The creation of a marine protected area will be analysed for a hypothetical fishery consisting of two species that interact under a predator–prey relationship. The prey (X_i) and predator species (Y_i) migrate between patches according to set dispersal relationships with no deaths or predation occurring during migration ($i = 1, 2$). The equations of motion for the biological system are given by (1) and (2):

$$\dot{X}_i = F(X_i) - aX_iY_i + z_i^x \tag{1}$$

$$\dot{Y}_i = F(Y_i, X_i) + z_i^y \tag{2}$$

where $F(X_i)$ and $F(Y_i, X_i)$ are the growth functions for prey and predator species in patch i, respectively, aX_iY_i is the level of predation in patch i, and z_i^x and z_i^y the dispersal relationships.

Harvest in the fishery is assumed to follow a Schaefer production function (1957) with 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 the catchability coefficient of species j in patch i, E_i^j the level of effort applied to species j in patch i, and J_i^j the level of biomass of species j in patch i ($i = 1, 2$).

Optimal biomass in each patch is found by solving the continuous time optimisation problem (see Appendix). The solution presented here is in generic form. With two patches and two species, four problems as set out in Equations (3), (4), and (5) must be solved simultaneously to derive the result. Optimal levels of biomass need to take into account the effects of dispersal in a metapopulation model. The objective functional (net social value – NSV) for one patch is given by Equation (3), 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, δ is the social discount rate, and all other variables as defined with subscripts indicating patch and superscripts indicating species.

$$\max \text{NSV} = \int_0^\infty e^{-\delta t}(p_i^j q_i^j w_i^j - c_i^j)E_i^j \cdot dt \tag{3}$$

$$\text{s.t}\ \frac{dJ_i^j}{dt} = F_i^j(\cdot) + z_i^j - q_i^j E_i^j w_i^j \tag{4}$$

$$0 \le E_i^j \le E_{i\max}^j \tag{5}$$

For mathematical convenience, the functions are assumed to be twice continuously differentiable over their relevant domain. The Hamiltonian of this problem, where λ is the co-state variable (shadow price of biomass), is given by:

$$H = [e^{-\delta t}(p_i^j q_i^j w_i^j - c_i^j) - \lambda(q_i^j w_i^j)]E_i^j + \lambda[F_i^j(\cdot) + z_i^j]\,. \tag{6}$$

Singular control occurs when the derivative of (6) with respect to the control variable (E_i^j) is set to zero. The solution to this in terms of the shadow price of biomass (λ) becomes:

$$\lambda = e^{-\delta t}\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right), \tag{7}$$

$$\frac{d\lambda}{dt} = -\delta e^{-\delta t}\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) + e^{-\delta t}\frac{d\left(p_i^j - \dfrac{c_i^j}{q_i^j w_i^j}\right)}{dj} \cdot \frac{dJ_i^j}{dt}. \tag{8}$$

From the Adjoint equation where Equation (7) has been used for λ:

$$\frac{d\lambda}{dt} = -\frac{dH}{dJ_i^j} = -e^{-\delta t}\left[\frac{c_i^j w_i^{j\prime} E_i^j}{w_i^j} + \left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right)[F_i^{\prime j}(\cdot) + z_i^{j\prime}]\right] \tag{9}$$

where $w_i^{j\prime}$, $z_i^{j\prime}$, and $F_i^{\prime j}(\cdot)$ are the first derivates of w_i^j, z_i^j, and $F_i^j(\cdot)$ with respect to biomass J_i^j. Solving simultaneously Equations (8) and (9) the optimal biomass is given when:

$$\delta = \frac{c_i^j w_i^{j\prime}[F_i^j(\cdot) + z_i^j]}{w_i^j(p_i^j q_i^j w_i^j - c_i^j)} + [F_i^{\prime j}(\cdot) + z_i^{j\prime}]. \tag{10}$$

The optimal level of biomass is found from Equation (10) and is equal to that in Clark (1990, p. 95) given that the dispersal terms (z_i^j and $z_i^{j\prime}$) are equal to zero. From Equation (10), the instantaneous internal rate of return (right-hand side) should be equal to the external rate of return (discount rate). The internal rate of return is affected by the dispersal of biomass. In particular, the biological return $F_i'^{j}(\cdot) + z_i^{j\prime}$ and the effect of biomass on rent (first term on right-hand side – see Grafton *et al.* 2004b, p. 113) is affected by the dispersal of stock. Further, if z_i^j is positive (that is, an inflow), the optimal level of biomass in the exploited patch is lower than that described by Clark (1990, p. 95). To maximise the net present value of the patch, 'imported' biomass is substituted for local biomass. Optimal biomass in one patch is then found by solving all equations simultaneously.

The predator–prey interaction takes the form described by Ströbele and Wacker (1995) where limits to biomass are defined by carrying capacity and the level of predation and the growth of species are assumed to be logistic. Using this relationship, the equations of motion are given by:

$$\dot{X}_i = X_i\left[r\left(1 - \frac{X_i}{K_i}\right) - aY_i\right] + z_i^x - q_i^x E_i^x X_i \tag{11}$$

$$\dot{Y}_i = Y_i\left[s\left(1 - \frac{bY_i}{X_i}\right)\right] + z_i^y - q_i^y E_i^y Y_i \tag{12}$$

where r is the intrinsic growth rate, K_i the carrying capacity of patch i, a and b the predation parameters (assumed to be greater than zero), and all other variables as previously defined ($i = 1, 2$).

In the absence of harvest, the biomass of both species is strictly greater than that when harvest exists under most conditions. Thus, biomass will generally increase when a protected area is established given prior fishing.

Dispersal between the two subpopulations is assumed to be driven by either density-dependent or sink-source flows. Density-dependent dispersal is defined as movements that are caused by relative differences in patch population density (Sanchirico and Wilen 2001). The form of this dispersal is as defined by Conrad (1999), and is shown in Equations (13) and (14) taking the prey species as the example:

$$z_1^x \equiv g^x\left(\frac{X_2}{K_2} - \frac{X_1}{K_1}\right) \tag{13}$$

$$z_2^x \equiv g^x\left(\frac{X_1}{K_2} - \frac{X_2}{K_2}\right) \tag{14}$$

Sink-source flows are unidirectional, and are often the result of oceanographic processes such as currents, temperature, and winds. The relationship is characterised by an equilibrium flow occurring between the patches (Sanchirico and Wilen 2001). A sink-source flow is given in Equation (15) for the source patch, and Equation (16) for the sink patch.

$$z_1^x \equiv -g^x\left(\frac{X_1}{K_1}\right) \tag{15}$$

Table 1 Steady-state effort and harvest relations – density-dependent dispersal

Effort	Harvest
$E_i^x = \frac{g^x}{X_i q_i^x}\left(\frac{X_j}{K_j} - \frac{X_i}{K_i}\right) + \frac{1}{q_i^x}\left[r\left(1 - \frac{X_i}{K_i}\right) - aY_i\right]$	$h_i^x = X_i\left[r\left(1 - \frac{X_i}{K_i}\right) - aY_i\right] + g^x\left(\frac{X_j}{K_j} - \frac{X_i}{K_i}\right)$
$E_i^y = \frac{g^y}{Y_i q_i^y}\left(\frac{bY_j}{X_j} - \frac{bY_i}{X_i}\right) + \frac{s}{q_i^x}\left(1 - \frac{bY_i}{X_i}\right)$	$h_i^y = sY_i\left(1 - \frac{bY_i}{X_i}\right) + g^y\left(\frac{bY_j}{X_j} - \frac{bY_i}{X_i}\right)$

Table 2 Steady-state effort and harvest relations – sink-source dispersal

Effort	Harvest
Source Patch	**Source Patch**
$E_i^x = \frac{r}{q_i^x}\left(1 - \frac{X_i}{K_i}\right) - \frac{a}{q_i^x}Y_i - \frac{g^x}{q_i^x K_i}$	$h_i^x = rX_i\left[\left(1 - \frac{X_i}{K_i}\right) - aY_i\right] - g^x\frac{X_i}{K_i}$
$E_i^y = \frac{s}{q_i^y}\left(1 - \frac{bY_i}{X_i}\right) - g^y\frac{b}{q_i^y X_i}$	$h_i^y = sY_i\left(1 - \frac{bY_i}{X_i}\right) - g^y\frac{bY_i}{X_i}$
Sink Patch	**Sink Patch**
$E_j^x = \frac{r}{q_j^x}\left(1 - \frac{X_j}{K_j}\right) - \frac{a}{q_j^x}Y_j + \frac{g^x X_i}{q_j^x K_i X_j}$	$h_j^x = rX_j\left[\left(1 - \frac{X_j}{K_j}\right) - aY_j\right] + g^x\frac{X_i}{K_i}$
$E_j^y = \frac{s}{q_j^y}\left(1 - \frac{bY_j}{X_j}\right) + g^y\frac{bY_i}{q_j^y X_i Y_j}$	$h_j^y = sY_i\left(1 - \frac{bY_j}{X_j}\right) + g^y\frac{bY_i}{X_i}$

$$z_2^x \equiv +g^x\left(\frac{X_1}{K_1}\right) \tag{16}$$

Under a density-dependent dispersal relationship, the steady-state levels of harvest and effort are given by the equations presented in Table 1. Steady-state levels of effort and harvest were found by replacing z_i^x and z_i^y with the density-dependent dispersal equations.

Steady-state levels of harvest and effort for both species were determined for the sink-source dispersal system and are presented in Table 2.

The risk of stock collapse is introduced into the model using Ito's lemma as set out by Li (2000). Li examines marine park creation in the context of uncertainty where the protected area offsets the risk of an uncertain event. If Π^* represents the steady-state rent generated from the fishery in any given year and δ is the social discount rate, then Π^*/δ is the net social value of the resource in the absence of stock collapse. The creation of a marine protected area is assumed to reduce the risk of stock collapse through reductions in demographic stochasticity (accidental variation in birth and death rates and sex ratio), environmental stochasticity (variations in the biological and physical environment that influence food and habitat availability), catastrophes that occur on an infrequent timescale (may require population size to be such as to ensure survival against sporadic events), and genetic stochasticity (a sufficient gene pool is required to allow species to adapt to changing environments) (Bulte and van Kooten 2001). The risk of collapse with a marine protected area over a small time interval is represented by Li (2000), and modified such that:

$$\phi = \left[\left(\frac{T - k_2}{T}\right)^3\right]\eta \cdot dt \tag{17}$$

where T is the total fishery area and k_2 the area set aside for protection. The risk of stock collapse, η, is modelled as a Poisson event (Pindyck and Rubinfield 1986; Li 2000; Bulte and van Kooten 2001). Unlike in Li (2000), the offsetting effect of protected area creation is examined in the context of a fishery with heterogenous environments, where the biomass of two species flows between patches based on set dispersal relationships. Using Equation (19), the net social value (NSV) of the fishery, incorporating the risk of stock collapse, given the fishery generates Π^* each season prior to collapse and zero after, is said to follow a Poisson process θ through time:

$$dNSV = -NSV \cdot d\theta \tag{18}$$

where

$$d\theta = \begin{cases} 0 & \text{with probability } 1 - \left[\left(\frac{T - k_2}{T}\right)^3\right]\eta \cdot dt \\ 1 & \text{with probability } \left[\left(\frac{T - k_2}{T}\right)^3\right]\eta \cdot dt \end{cases} \tag{19}$$

Using Ito's lemma in relation to a jump process (Dixit and Pindyck 1994, p. 85; Li 2000), the change in NSV over the period dt can be decomposed into a season's rent plus the value of the potential stock loss given collapse:

$$NSV = \frac{\Pi^*}{\delta + \left[\left(\frac{T - k_2}{T}\right)^3\right]\eta} \tag{20}$$

If the risk of stock collapse were ignored, the fishery would be overvalued and thus would underperform compared with a similar class of risky assets.

3.1 The stochastic model

In order to capture the effect of random fluctuations in fish populations, growth rates are assumed to be stochastic (Conrad 1999; Pezzey *et al.* 2000; among others). The randomness in growth rates will influence both harvest and effort as fishers respond to variable changes in biomass. The new growth rates, which are independent of patch size, are denoted by r_z and s_z, where r_z is the stochastic intrinsic prey growth rate that follows a triangular distribution with mean 0.8 and variance 0.07, and s_z is the stochastic intrinsic predator growth rate that follows a triangular distribution with mean 0.6 and variance 0.05. The new equations of motion are given by Equations (21) and (22), ($i = 1, 2$):

$$\dot{X}_i = X_i\left[r_{zi}\left(1 - \frac{X_i}{K_i}\right) - aY_i\right] + z_i^x - q_i^x E_i^x X_i \tag{21}$$

$$\dot{Y}_i = Y_i\left[s_{zi}\left(1 - \frac{bY_i}{X_i}\right)\right] + z_i^x - q_i^y E_i^y Y_i \tag{22}$$

The only difference between Equations (21) and (22) and Equations (11) and (12) in the previous section is the replacement of the deterministic intrinsic patch growth rates (r_i and s_i) with the stochastic patch growth rates (r_{zi} and s_{zi}). As such, all the equations for effort and harvest presented in Tables 1 and 2 remain the same given the replacement of growth rates.

4. Protected area creation – a simulation approach

Steady states for the hypothetical fishery were simulated in order to identify the effects of marine protected area creation. In the stochastic model, the 'steady state' is defined as the state where all variables (harvest, effort, biomass and rent) have a constant mean and variance. The fishery is assumed to be 100 units of carrying capacity in size. A total of 10 000 draws were taken from the five random variables in the model (r_{z1}, r_{z2}, s_{z1}, s_{z2} and η) based on different correlation scenarios for a range of different protected area sizes. The correlation scenarios examined were: (i) no correlation (uncorrelated); (ii) r_{z1} and r_{z2}, and s_{z1} and s_{z2} perfectly correlated (species correlated); and (iii) r_{z1} and s_{z1}, and r_{z2} and s_{z2} perfectly correlated (patch correlated). Further, a series of different management structures were examined, namely, open access, optimal steady-state controls, 75 per cent of optimal steady-state controls, and 50 per cent of optimal steady-state controls. The latter three management structures allow an analysis of the resource rent derived from fishery resources. However, as exploitation rent is dissipated under open-access, the effects examined were on harvests and effort.

4.1 Open-access exploitation

Under open-access exploitation, the creation of a marine protected area will not influence the net social value of the fishery; however, it will influence the level of economic activity that is conducted in the fishery.

Given a density-dependent dispersal relationship, mean total harvests of both predator and prey species fall given the creation of a protected area; however, mean total biomass for both species increased. Steady-state harvest variation in the fishing ground increased under all correlations for predator and prey species, with the exception of predator harvest with patch-correlated growth. Despite this, steady-state total harvest variation for the fishery fell for both species because of the reduced stock collapse risk, as the chance of a zero extreme was reduced.

The establishment of a marine protected area led to increased dispersion. Internal patch equilibria determine the flow of biomass from the protected area. As this flow is a residual, the flow is more variable than harvesting the underlying biomass, making harvest more variable. This effect was not seen for the predator species under patch-correlated growth rates as predator numbers were kept ‘in check’ through synchronised population changes. This limited the flow of predators from the protected area.

Under sink-source dispersal, mean total prey harvest fell in absolute numbers under all correlation scenarios. Steady-state total harvest variation for both species in the fishery and in the open patch decreased as a result of creating a marine protected area of any size. It appears that the flow of both species biomass that occurs irrespective of the density in the fishing grounds offsets low extremes in catch. This result was not seen for predator species where steady-state total harvest variation in the fishery and in the open patch increased as a result of the marine protected area, despite an increase in absolute harvests.

4.2 Controlled resource extraction

Three management structures were examined in which access to fishery resources was limited: (i) optimal steady-state management; (ii) when biomass in the patches is maintained at 75 per cent of the optimal steady-state level; and (iii) when biomass is maintained at 50 per cent of the optimal steady-state level (or at an open-access level depending on whether fishing would take place or not).

4.2.1 Density-dependent dispersal

The creation of a marine protected area has the potential to affect the resource rent obtained from the fishery first through influencing the level of effort and harvest through influencing the level of biomass in the fishing ground, and second through reducing the risk of stock collapse and normal environmental fluctuations. Given optimal steady-state management, a marine protected area may increase resource rent. The opportunity cost in terms of net social welfare (derived from both species) of establishing a marine protected area in a fishery is shown in Figure 1 for the three controlled management structures. The creation of a marine protected area has a negative opportunity cost for small-sized protected areas, that is a gain for society. Given this, the creation of a marine protected area can be optimal. For the hypothetical fishery analysed,

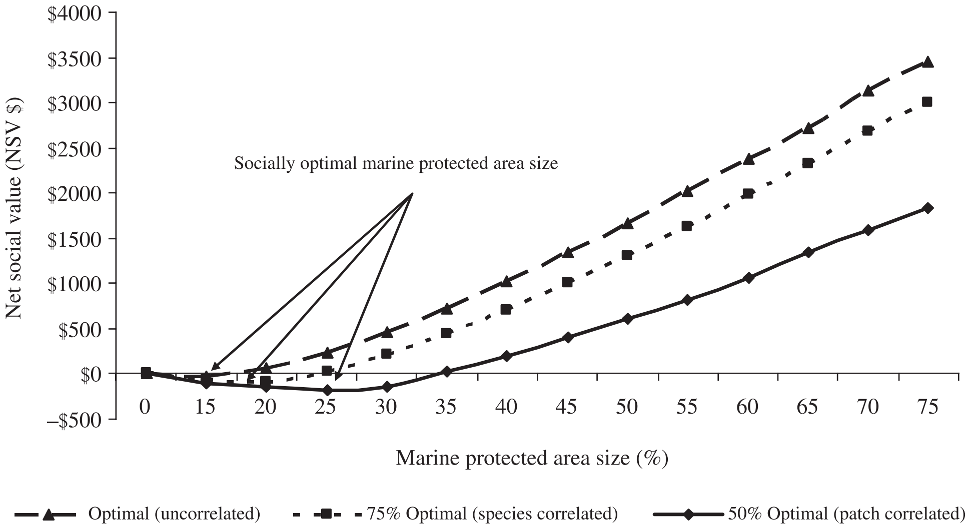

Figure 1 Opportunity costs of establishing marine protected areas, density-dependent flow.

Notes: $r_{z1} = r_{z2} = 0.8$, $s_{z1} = s_{z2} = 0.6$, $g_x = g_y = 2$, $q_x = 0.01$, $p_x = 20$, $p_y = 30$, $c_x = 1.5$, $c_y = 1$, $b = 2$, $a = 0.02$.

a protected area of 15 per cent maximised the mean net social welfare for a fishery with optimal steady-state controls, with protected areas of close to 20 and 25 per cent maximising the mean net social value of fisheries with 75 and 50 per cent optimal steady-state controls, respectively.

The protected area can be of a certain size such that no opportunity cost exists (the points where the curves in Figure 1 cross the x-axis). From this result, marine environments can be protected for other uses with no cost to the fishery. The opportunity cost can be used to represent the ‘supply’ curve for marine protected areas for a fishery. Other values derived from fishery resources, such as non-use values, can be incorporated to determine the optimal protected area size for society by determining the intersection point between the ‘supply’ of and ‘demand’ for protected areas.

Despite protected areas having the potential to improve the value of the fishery for society, establishment may have some adverse effects for current fishery operators. Because of changes in steady-state outcomes being examined, it is not possible to examine effects of displaced effort from the protected area in the short term on the surrounding fishery. However, changes in steady-state effort levels provide an indication of the effects on different fisheries. Increases in resource rent created through protected area establishment mean that current levels of effort may be too great given fishery characteristics. Under 50 per cent optimal steady-state controls, the establishment of an optimal protected area size of 25 per cent of the fishery led to a 38 per cent fall in the level of effort applied to prey species, and a 17 per cent increase in effort applied to predator species (average results for all correlation scenarios). Similar changes in effort were seen for a protected area of 20 per cent of the fishery under 75 per

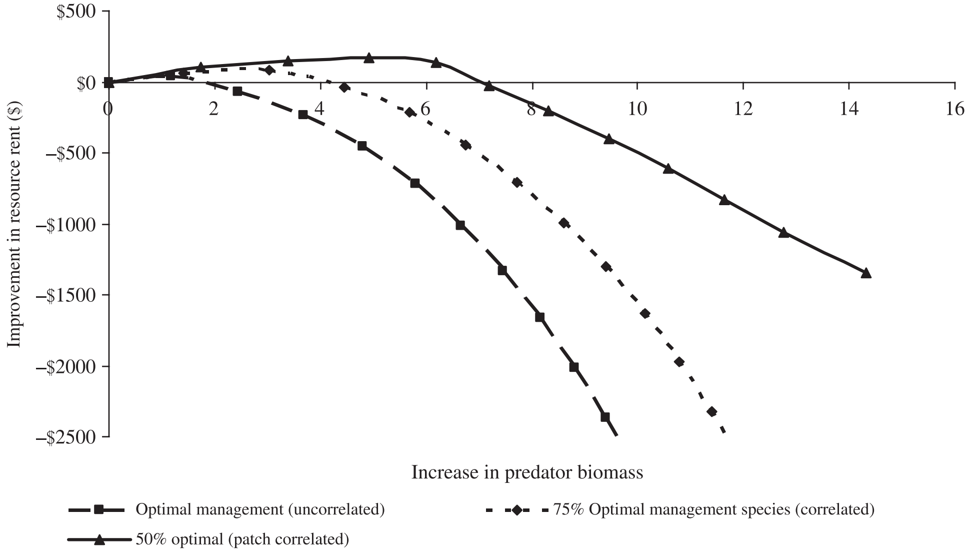

Figure 2 Predator biomass preserved versus improvement in net social value density-dependent flow.

Notes: $r_{z1} = r_{z2} = 0.8$, $s_{z1} = s_{z2} = 0.6$, $g_x = g_y = 2$, $q_x = 0.01$, $p_x = 20$, $p_y = 30$, $c_x = 1.5$, $c_y = 1$, $b = 2$, $a = 0.02$.

cent optimal steady-state controls, and for optimal steady-state controls. Under these management structures, effort applied to the predator species was affected less (or benefited) by protected area establishment.

The cost of increasing biomass in the fishery was examined for the three management structures and is depicted in Figure 2. The creation of a marine protected area led to an increase in the total biomass of both species within the fishery. Given 50 per cent optimal steady-state controls and patch-correlated growth rates, protection of 7 units of predator biomass occurs at no cost to society in terms of mean net social value; however, the protection of 10 units occurs at a cost of $500. As expected, the change in mean net social value of increasing biomass of both species under optimal steady-state controls is almost always negative, with greater positive results for the less-controlled fisheries.

The correlation of species growth rates had varying effects on the steady-state variation of rent and harvests of both species in the fishery. For all management structures, uncorrelated growth rates resulted in the greatest fall in mean steady-state total resource rent variation, with the least fall occurring under patch-correlated growth rates (see Figure 3). This result is consistent with Bulte and van Kooten's (1999) results that when the stocks move in unison (with positive correlation), the exposure to risk of the system also increases. As for open access, uncorrelated growth rates mean that extremes in the population of both species could be offset through dispersal, thus minimising the possibility of low extremes having a greater effect than the exaggeration of high extremes. When the growth rates of species or the growth rates within

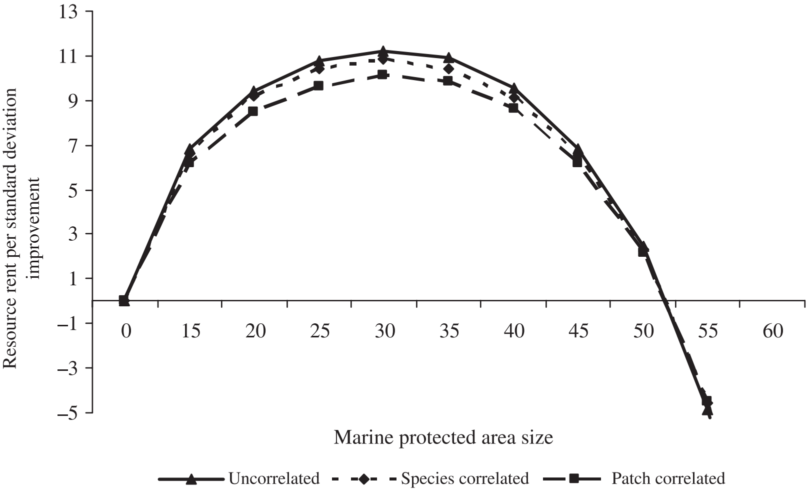

Figure 3 Net social value per standard deviation under 75 per cent optimal steady-state management.

Notes: $r_{z1} = r_{z2} = 0.8$, $s_{z1} = s_{z2} = 0.6$, $g_x = g_y = 2$, $q_x = 0.01$, $p_x = 20$, $p_y = 30$, $c_x = 1.5$, $c_y = 1$, $b = 2$, $a = 0.02$.

the patches were correlated, the potential to offset extremes was lessened as either lows occurred at the same time, or dispersal was lessened due to within-patch dynamics. In contrast to the results obtained by Conrad (1999), protected areas of close to 30 per cent of the fishery had the greatest reduction in net social value per standard deviation. Further, smaller-sized protected areas reduced the net social value per standard deviation with increases for protected area sizes above 50 per cent.

Steady-state variation in the harvest of both species in the open patch fell for all correlations. This is unlike the result obtained under open access, where harvest variation increased. Given that controls on fishing effort existed, periods of very high effort were prevented, thus reducing high extremes of harvests.

4.2.2 Sink-source dispersal

Under a sink-source dispersal relationship, biomass of both species continues to flow between the patches irrespective of the population density in the sink patch. In this scenario, the area closed was assumed to be the source patch. If the sink patch was closed, results for the source patch were as if there were no metapopulation relationship in the fishery – a closed system (see Sanchirico and Wilen 2001).

As dispersal between patches is not influenced by the level of biomass in the fishing ground, periods of high growth of both species will not limit the level of dispersal, potentially exaggerating high extremes. Given this, the mean total resource rent and harvests before and after the creation of a protected area were both more variable than under a density-dependent dispersal.

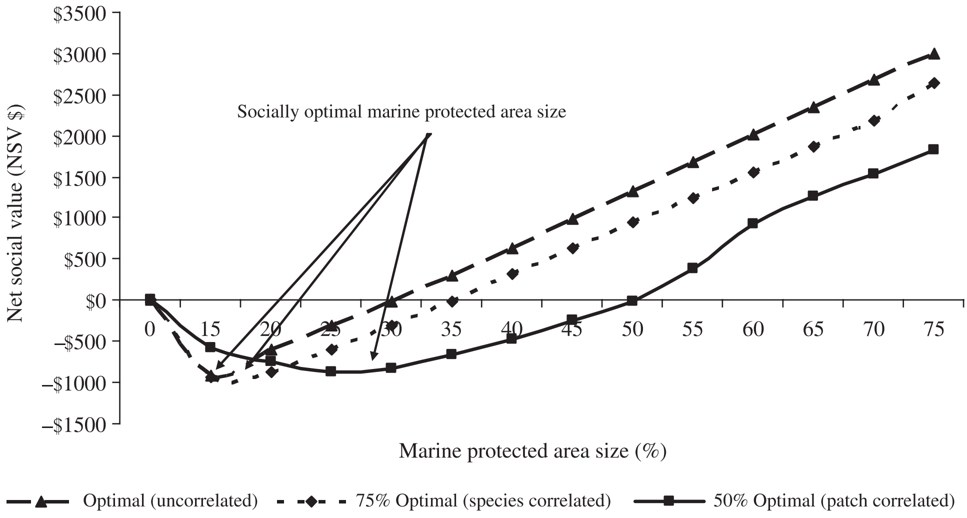

Figure 4 Opportunity costs of establishing marine protected areas, sink-source dispersal.

Notes: $r_{z1} = r_{z2} = 0.8$, $s_{z1} = s_{z2} = 0.6$, $g_x = g_y = 2$, $q_x = 0.01$, $p_x = 20$, $p_y = 30$, $c_x = 1.5$, $c_y = 1$, $b = 2$, $a = 0.02$.

The socially optimal proportion of the fishing ground to be protected, and improvement in mean total resource rent, was higher than under a density-dependent dispersal (Figure 4). For a fishery under optimal steady-state management controls, a protected area of 15 per cent maximised the mean resource rent attainable, with a protected area of close to 30 per cent maximising mean resource rent for a fishery under 50 per cent optimal steady-state controls. Effects on effort levels under sink-source dispersal were similar to those seen given density-dependent dispersal. Effort applied to predator species given optimally sized protected areas increased as a result of protected area creation, whereas it decreased for prey species.

When growth rates were uncorrelated, the fishery had the greatest reduction in mean total resource rent and harvest variation of both species as a result of protected area creation. Further, given that some controls were placed on fishing activity, mean harvest variation of both species in the open patch fell as a result of protected area creation.

The cost of protecting the biomass of both species within the fishery is given in Figure 5. For small increases in mean biomass for either species, the mean net social value improved sharply. As the level of biomass of either species increased, the cost increased rapidly (or improvement in fishery value decreased rapidly).

5. Policy implications

Marine protected areas have been suggested as a hedge tool for fisheries managers against uncertain stock movements. The potential reduction in stock collapse risk through the creation of a protected area in a fishery

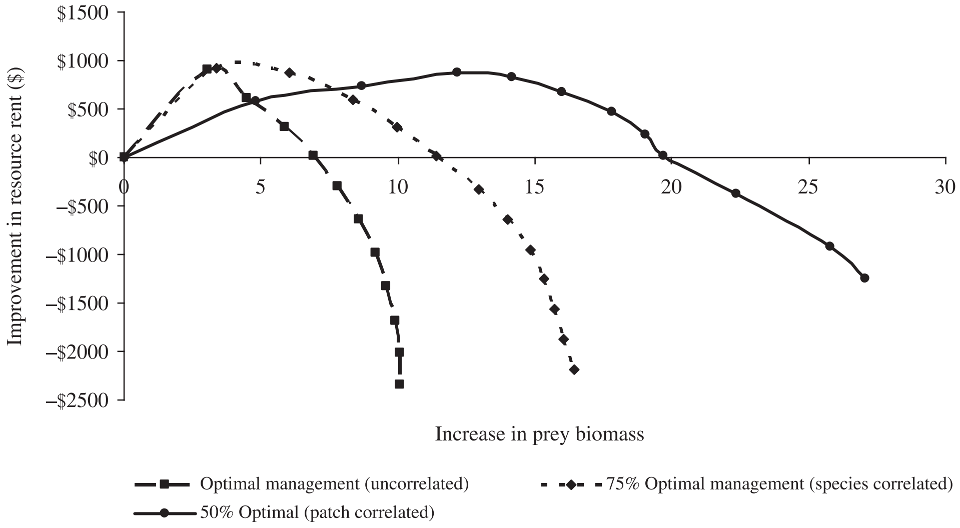

Figure 5 Prey biomass preserved versus improvement in net social value, sink-source dispersal.

Notes: $r_{z1} = r_{z2} = 0.8$, $s_{z1} = s_{z2} = 0.6$, $g_x = g_y = 2$, $q_x = 0.01$, $p_x = 20$, $p_y = 30$, $c_x = 1.5$, $c_y = 1$, $b = 2$, $a = 0.02$.

characterised by spatially heterogeneous environments has been shown to lead to an increase in harvest risks for the exploiting industry depending on the management. This result differs from those presented by other studies that were based on single stock and homogenous environments harvested under open-access exploitation (e.g., Conrad 1999; Pezzey *et al.* 2000; Hannesson 2002). The results from this study are consistent with the findings from Grafton *et al.* (2005) in the sense that small-sized protected areas can yield benefits to fisheries in instances where populations are not overly exploited. Despite this, the predator–prey interaction has some extra effects not seen in the modelling of single species.

From the results, it can be seen that the establishment of protected areas in a fishery characterised by an uncertain stock collapse event had the potential to improve the net social value of the fishery. From this, protected areas can be used as a tool to optimally manage fishery resources. However, for marine protected areas to yield a positive outcome, they must reduce the risk of stock collapse from occurring. In this paper, the risk of stock collapse was assumed to be a diminishing function of protected area size because of the ability of a protected area to preserve both biomass levels and the ecological functioning of the marine environment. Given less extremes of uncertainty, protected areas may still have the potential to improve optimal steady-state returns through their ability to smooth fluctuations in harvests and effort caused through normal environmental stochasticity.

The predator–prey interaction complicates dispersal patterns, creating a situation where dispersal becomes an ‘excess’ effect, a residual to the own-patch equilibrium. The excess stock movements are determined by the variation in the growth rates of species within the patch, and are therefore more variable than harvest within the patch itself. With harvest limited to one patch, the importance of dispersal to total harvests increases. The increased importance of a more variable stock increases the variation of the entire harvest. This effect is exaggerated in the absence of stock collapse risk where the creation of a marine protected area has the potential to increase harvest variation under both controlled and uncontrolled resource use (Greenville 2004).

Protected areas were seen to perform best (in terms of the hedge effect) when the protected area and fishing ground were connected through density-dependent dispersal patterns, and species growth rates were uncorrelated. Uncorrelated growth rates allowed for the greatest reduction in both mean steady-state harvests and resource rent as it provided the greatest hedge effect. As density-dependent flows limited high extremes, they also reduced variation in the system. In a policy sense, if protected areas can be established in patches with independent dynamics, where stocks flow to and from the fishing ground, they are likely to maximise the benefits created.

The predator–prey interaction is exacerbated in the case of predator harvests under sink-source flows. Unlike for density-dependent dispersal, there is no smoothing of dispersal in periods of high growth in the open patch, as dispersal does not depend on relative stock densities. Thus, the variation in the dispersal flow is only dependent on the stock interaction within the source patch, creating a more variable flow than under a density-dependent dispersal.

Under open-access exploitation, mean harvest variation in the open ground increased, but mean total harvest variation decreased (as pre-protected area mean harvest variation in patch 2 was large). The creation of a marine protected area benefits society in the sense that it improves the reliability of fish harvests, but for the remaining fishers in the open patch their harvests are more variable than otherwise would be the case. Given this, fishers may resist the creation of a protected area because of the potential increase in harvest variation and resultant loss of livelihood.

As most fisheries are not subject to open-access exploitation, the results from controlled resource extraction are important for policy-makers. The value of using a marine protected area for fisheries management is improved through the use of other controls placed on fishers' activities. Although the use of protected areas as the sole tool of management improves the biomass in the protected area, it does not necessarily improve harvests or even lower harvest variation for fishers in the surrounding fishing grounds. In the presence of the use of some controls on fishing activity, harvest variation in the fishing ground fell. The cause of the reduced harvest variation was through the reduced ability to fish extremes in biomass. The use of a protected area lessened the potential for low extremes in harvests, whereas the management controls lessened the potential for high extremes.

In terms of effort levels under controlled resource extraction, protected areas are likely to have different distributional effects on fisheries that target different species. Optimal-sized protected areas had a lesser (or beneficial) effect on effort levels in predator fisheries compared with prey fisheries. As predators in the hypothetical fishery were fished relatively more intensely because of price pressures, the protected area led to a significant increase in predator numbers, both improving predator flow from the protected area and reducing prey numbers. These distributional effects are likely to lead to opposition from certain fishers to the establishment of protected areas despite the potential for all parties to be better off. Grafton and Kompas (2005) suggest that 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 redistribution of the potential benefits. Such compensation schemes should be mindful of the overall costs and benefits, including the monitoring and enforcement costs of protected area establishment.

6. Concluding comments

In this study, it has been shown that the use of a protected area has the potential to improve the resource rent obtained from the fishery given management controls. Further, changes in the variation of mean harvests and rent were dependent on the management controls, correlation of species growth rates, and dispersal relationship.

Improvements in biomass levels of both species under open-access exploitation may come at a cost. The cost was seen through an increase in the variation of mean harvests in open fishing grounds. Total mean harvest fell and the steady-state harvest variation increased. Opposition to the creation of protected areas under this management structure is likely to be strong. However, in the case of structures where controls existed, there is potential for protected area creation to be consistent with fishers' interests, as creation improved both the total mean resource rent and decreased steady-state harvest variation in the open fishing ground. It is more likely that fisheries controlled in some way would adopt marine protected areas as a tool for management.

The 'demand side' of protected areas was not considered; that is, the non-use values associated with the protection of habitat and species were not specifically analysed. Instead, the focus was placed on the 'supply side' issues; that is, the cost to society in the form of forgone fishing rent. Despite this, a framework has been developed that could be used to assess the optimal use of protected areas not only in terms of the level of resource rent derived from the fishing industry, but also from their broader use.

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Appendix: optimal harvest of a metapopulation

Variables:
δ = discount rate, t = time, p_i^j = price of species j in patch i
q_i^j = catchability of species j in patch i
w_i^j = biomass of species j in patch i
$w_i^j = J_i^j + z_i^j$
z_i^j = dispersal function (assumed to be a function of j)
E_i^j = effort of species j in patch i
c_i^j = cost of effort of species j in patch i
$F_i^j(\cdot)$ = growth function of species j in patch i
Optimal harvest occurs at maximum net social value which defines the objective functional (assuming all functions are twice continuously differentiable over their relevant domain).

$$\max \text{NSV} = \int_0^\infty e^{-\delta t}(p_i^j q_i^j w_i^j - c_i^j)E_i^j \cdot dt$$

$$\text{s.t } \frac{dJ_i^j}{dt} = F_i^j(\cdot) + z_i^j - q_i^j E_i^j w_i^j$$

$$0 \le E_i^j \le E_{i\max}^j$$

Define the Hamiltonian:

$$H = [e^{-\delta t}(p_i^j q_i^j w_i^j - c_i^j) - \lambda(q_i^j w_i^j)]E_i^j + \lambda[F_i^j(\cdot) + z_i^j]$$

First, the control variable E_i^j must be such so as to maximise the value of the Hamiltonian:

$$\frac{dH}{dE_i^j} = e^{-\delta t}(p_i^j q_i^j w_i^j - c_i^j) - \lambda(q_i^j w_i^j) = 0$$

$$\lambda = e^{-\delta t}\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) \tag{A.1}$$

Find $d\lambda/dt$ from Equation (A.1)

$$\frac{d\lambda}{dt} = -\delta e^{-\delta t}\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) + e^{-\delta t}\frac{d\left(p_i^j - \dfrac{c_i^j}{q_i^j w_i^j}\right)}{dj} \cdot \frac{dJ_i^j}{dt}$$

Therefore:

$$\frac{d\lambda}{dt} = -\delta e^{-\delta t}\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) + e^{-\delta t} \cdot \frac{c_i^j w_i^{j\prime}}{q_i^j w_i^{j2}} \cdot \frac{dJ_i^j}{dt}$$

Substitute in the constraint for dJ_i^j/dt

$$\frac{d\lambda}{dt} = -e^{-\delta t}\left[\delta\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) - \frac{c_i^j w_i^{j\prime}(F_i^j(\cdot) + z_i^j)}{q_i^j w_i^{j2}} + \frac{c_i^j w_i^{j\prime} E_i^j}{w_i^j}\right] \tag{A.2}$$

Second, from the maximum condition, the existence of an adjoint variable is such that:

$$\frac{d\lambda}{dt} = -\frac{dH}{dJ_i^j}$$

$$\frac{dH}{dJ_i^j} = e^{-\delta t}(p_i^j q_i^j w_i^{j\prime})\lambda(q_i^j w_i^j)]E_i^j + \lambda[F_i^{\prime j}(\cdot) + z_i^{j\prime}]$$

Substitute Equation (A.1) for λ:

$$\frac{dH}{dJ_i^j} = e^{-\delta t}\left[\frac{c_i^j w_i^{j\prime} E_i^j}{w_i^j} + \left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right)[F_i^{\prime j}(\cdot) + z_i^{j\prime}]\right] \tag{A.3}$$

Now, Equation (A.2) = –(A.3) (the maximum condition)

$$\begin{aligned}
-e^{-\delta t}&\left[\delta\left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right) - \frac{c_i^j w_i^{j\prime}(F_i^j(\cdot) + z_i^j)}{q_i^j w_i^{j2}} + \frac{c_i^j E_i^j}{w_i^j}\right] \\
&= -e^{-\delta t}\left[\frac{c_i^j w_i^{j\prime} E_i^j}{w_i^j} + \left(p_i^j - \frac{c_i^j}{q_i^j w_i^j}\right)[F_i^{\prime j}(\cdot) + z_i^{j\prime}]\right] \\
\delta &= \frac{c_i^j w_i^{j\prime}(F_i^j(\cdot) + z_i^j)}{w_i^j(p_i^j q_i^j w_i^j - c_i^j)} + [F_i^{\prime j}(\cdot) + z_i^{j\prime}]
\end{aligned}$$

This equation is quadratic in J_i^j; however, it only has one rational root that satisfies positive and real biomass. The addition of extra patches does not increase the polynomial order of these functions if dispersal relationships are as defined.