A Bioeconomic Model of a Marine Park

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University of Sydney, NSW, 2006

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Abstract

A spatial bioeconomic model of a fishery will be used to investigate the effect of creating a marine park in a heterogeneous environment. Focus will be placed on the relevant biological and economic conditions needed to provide a benefit to both fishers and conservationists alike. The fishing environment will be one of limited entry to better simulate the conditions which exist in many developed nations. Fishers will be assumed to operate across patches in which the fish stocks are linked via either sink-source or density dependant spatial relationships.

Keywords: Bioeconomic, marine protected area, fisheries.

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1. Introduction

Australia's economic exclusion zone extends 200 nautical miles offshore with additional areas surrounding territorial islands and Antarctica. As the Australian continent is comprised of the one sovereign country, the ocean zone under Australia's control encompasses a wide range of habitats and oceans. Australia's economic exclusion zone incorporates parts of the Pacific, Indian and Southern oceans, and as it spans more than 40 degrees of latitude, it covers tropical, temperate and Antarctic ecosystems (Alder and Ward 2001). This large scale means that Australia has under its control an enormous stock of biodiversity, and hence the responsibility to manage this stock in an ecologically sustainable manner.

Management of a fish resource, be it single or multi species, is difficult due to the uncertainty attached to the biology and interaction of fish species (Conrad 1999). Marine parks (also called reserves or sanctuaries) have been called a hedge strategy against the imperfect ability to manage stocks and regulate fishers (Conrad 1999). No-take marine parks offer an opportunity to preserve all the ecological processes that occur within a certain habitat. These opportunities are often impossible under sustainable fishing structures. Further, a reason attributed to the lack of marine area protected for conservation outcomes is believed to be due to the lack of recognition that marine areas, along with terrestrial areas, can be degraded by human activities (Boersma and Parrish 1999).

The initial economic analyse conducted of marine resources were primarily concerned with extraction costs – Ricardian limits (cost limits) to production, and the question of Malthusian (absolute) limits was ignored (Smith and Wilen 2002). However, biologists and economists have seen that much of the threat to marine production is due to absolute limits; these limits have been reached in some cases and are close to being reached in others due to over exploitation.

Although marine parks are favoured for there management simplicity, it has been argued by some authors that they achieve no economic benefit or even any conservation benefit. Hannesson (2002) argues that without changes to the incentives faced by fishers which lead to over capitalisation and rent dissipation under open access, no economic or conservation goal can be achieved. The closure of one area of a fishery can lead to an increase in the biomass in that area, with the level determined by the rate of migration/dispersal from that zone. However, the spill over of biomass provides an incentive to further attract fishers to the non-protected areas, reducing the conservation goal of the park.

Marine parks offer policy makers an alternative to control policies aimed at altering individuals' behaviour. These policies aim to modify the actions of stakeholders either directly or indirectly through market mechanisms but can lead to inefficiencies (Boersma and Parrish 1999). On the global scale, there are close to 8000 established terrestrial protected areas covering over 750 million hectares which accounts for only 5.1 percent of the world's land surface area (Boersma and Parrish 1999). In contrast, marine protected areas (although the true nature of protection is unclear due to inconsistencies in the definition of a marine protected area) only account for close to 1 percent of the world's marine area (Boersma and Parrish 1999).

The purpose of this paper is to examine the impact of marine protected areas on an exploiting industry. The factors (both biological and economic) required for there to be a 'double gain' will be examined in the context of a predator prey stock interaction bioeconomic model. Previous studies have examined the impact of marine protected areas under open access and limited entry (Hannesson 2002, Sanchirico and Wilen 2001, Sanchirico and Wilen 2000 and others), however, none of these studies have examined a range of institutional structures in a multi-product fishery.

The structure of this paper follows. In the following section, the existing institutional arrangements will be briefly discussed, in section 3 biological constraints will be examined, in section 4 the bioeconomic model is presented. Section 5 presents the comparative statistics results from the model with their implications discussed in section 6.

2. Existing institutional arrangements

Fisheries in Australia have been managed in one way or another by governments from an early stage. The first attempts at management of NSW fisheries occurred in 1865 with the *Fisheries Act 1865*. The introduction of legislation governing fishing was brought about over concerns related to overfishing and the legislation allowed for the closure of fisheries. Since that time, governments have recognised the potential for exploitation of fishery resources and have introduced various institutional structures in order to regulate and control catch and effort within fisheries.

2.1 Fisheries in NSW

Most of the controls used by NSW fisheries are based on controlling fishing activity. These controls are based on input and output controls. Input controls are often criticised as an inefficient means of control. Limits to the use of one or a subset of inputs creates incentives to use other inputs more intensively as substitutes (Wilen 1979), and constant improvements in technology lead to the re-adjustment of controls creating uncertainty. Licensing is often used to manage various fisheries in order to limit the number of fishers with access to a fishery.

The use of marine parks as a fisheries management tool is a recent development in the history of fisheries management in NSW. Marine parks were established in NSW via the *Marine Parks Act 1997*. Since that time four marine parks have been established in four locations around the NSW coastal zone (Jervis Bay, Cape Bryon, Lord Howe Island and the Solitary Islands – Table 1). The purpose of the parks establishment is to preserve the biodiversity, and ecological functioning, of the marine environment in NSW. In order to manage these services, the government established the Marine Parks Authority.

The four parks listed in Table 1 are managed under different zoning plans. Some of the parks, namely Jervis Bay and the Solitary Island marine parks are zoned for shared use between commercial and recreational activities with areas of complete protection (no-take zones).

Table 1: Marine Parks in NSW

Marine Park	Area (ha)	Established
Cape Byron	22,700	November 1 2002
Jervis Bay	22,000	January 2 1998
Lord Howe Island	48,000	February 26 1999
Solitary Island	71,000	January 2 1998

2.2 Stakeholders

Fishers and conservationists are identified as the major stakeholders in the management of fishery resources in this study. Conservationists include all individuals who gain some benefit from the preservation of fish stocks. The establishment of a reserve under a limited entry fishery has the possibility to increase harvest, thus the new structure allows transactions (a possibility is a rent recovering transaction such as a tax, licence fee, etc) that lead to increased value from the resource.

Sanchirico and Wilen (1998) attribute the main opposition to marine reserves from fishermen to the 'not in my backyard' feeling that is expressed in issues such as waste disposal. Although, in some areas, fishermen see the benefits of a reserve being established, it may cover an area in which they have traditionally fished, or remove a substantial area of fishing grounds on which a fishing community once relied upon. This displacement is not unlike other structural change issues experienced in other sectors of the economy, and should be dealt with as such. If it is possible, through retraining and other programmes to alleviate some of the structural pain, then this should be a policy objective pursued by governments. However, care should be taken to ensure the policy outcome leads to a relatively efficient result.

The aim of using marine parks as a management tool is to preserve the biodiversity of a particular area. This conservation aim can be expressed in a political economy manner, by looking at changes in biomass (Sanchirico and Wilen 2001). In an exploited environment, the level of biomass of fish stocks will be below that of an 'untouched' environment. Thus, the establishment of a marine park should lead to an increase in the level of biomass thus achieving a conservation outcome. Other aims of marine protected areas focus on the maintenance of other ecosystem services. These services often have non-consumptive benefits or non-market values. These non-market values, however, will not be included in this analysis.

3. Biological issues

The management and analysis of fisheries resources (a renewable resource) has traditionally been based on the concept of maximum sustainable yield (Clark 1990, p.1). The concept is based on biological growth using the assumption that, given any level of stock below the environmental carrying capacity, a surplus production of biomass exists that can be harvested in perpetuity without altering the stock level (Clark 1990, p.1). From this, maximum sustainable yield is the point where the surplus production is the greatest.

The biomass of the fishery is exploited by an industry in which the level of harvest is a function of 'fishing effort', the catchability of fish and the stock level. Fishing effort is used as a term to represent the inputs used by fishers in a fishery. They range according to the type of fishery, but include things such as the number of vessel operating days. In the case of a common property renewable resource with no access controls, a stock externality exists, that is, individuals ignore the effect that their removals from a common stock have upon the future productivity of that stock (Conrad and Clark 1987, p.92). Given no controls, users will exploit the stock such that its level falls below that which maximises the net return from its use over time. This problem is often termed the problem of open access. Open access property rights differ from common property as with open access, no one or group of individuals control the rights to the resource, whereas under common property, society (a group of individuals) controls the rights to the resource and hence can influence the actions of individuals who use that resource.

Problems of open access institutional structures are that they lead to an efficiency loss and to the over exploitation of the underlying biological stock. This reduction in stock levels has impacts on other parts of the ecosystem, and if the species is lost, then there is a loss to society in the form of values associated with biodiversity. Many current management practices aim to reduce the level of catch to one which is sustainable (that is, a level of biomass such that the species does not become extinct) and to one which is more efficient. However, the controls used are based on analysis of a homogenous stock and do not take into account the external costs of fishing in different habitats. Thus, in a situation where heterogenous environments exist and comprise the area which is to be exploited by an industry, alternate spatial measures are needed to be used to efficiently manage the resource.

3.1 Heterogenous environments

Consider a fishery which is managed under a quota system. If the quota restrictions are optimal, the level of fishing will be reduced such that the marginal private benefit from fishing will be equal to the marginal social cost (See Godden 1997, p.137).

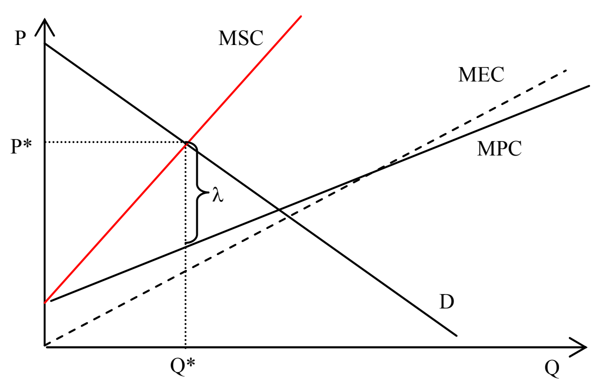


Figure 1: Quota setting for fishery

Marginal social cost (MSC) is the sum of the marginal private cost (MPC) to fishers from extracting the resource plus the marginal external cost to society (MEC) caused by overfishing (forgone rents) and damage to the environment from fishing activities (for example the destruction of habitat by trawl activities). For the fishery, MPC, MEC and MSC are the horizontal sum from each of the different areas (patches) in the fishery (Figure 1). The quota is such that for the fishery as a whole that the optimal level of catch (Q*), the price of fish (P*) and the quota price (λ).

Now consider that the fishery is comprised of two distinct patches where fishers in either patch are unable to influence price (that is they are price takers due to a large number of fishers). When these patches are homogenous, that is, the MPC and MEC in each patch are the same, thus resulting in the same MSC function for each patch, the quota price (λ) is sufficient to achieve the socially optimal outcome in each patch (Figure 2).

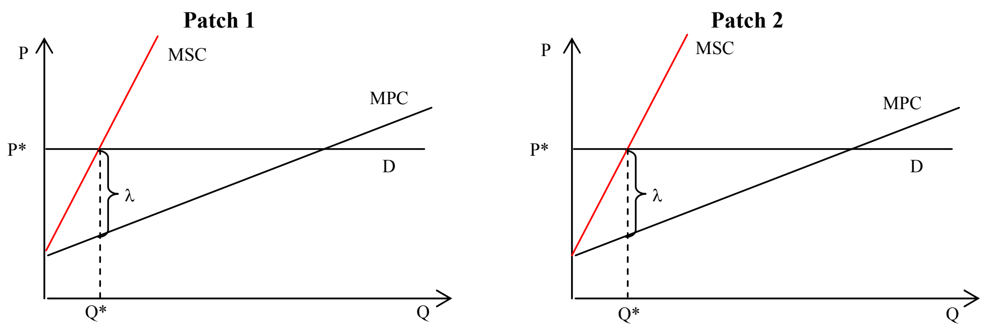


Figure 2: Quota in two homogenous patches

However, if the two patches were heterogenous and the quota price was determined for the fishery as a whole (Figure 1) then the resulting quota price may not be appropriate to achieve the socially optimal outcome. Consider the case where one patch is of superior biological character to the other (Patch 2). In this case, the MPC of fishing is lower due to the higher productivity of stock and subsequent greater catchability. Despite this, the MEC of fishing is greater as impacts on the environment lead to greater losses in habitat and biodiversity. Under this case, it is possible for the quota price to lead to a situation where the socially optimal outcome is not obtained, as greater fishing occurs in the high productivity patch than is desirable, and less fishing occurs in the low productivity patch than desirable (Figure 3). As such, a spatial control is required to achieve the socially desirable outcome. This could take the form of zoning the fishery and using existing management controls, or using a marine protected area.

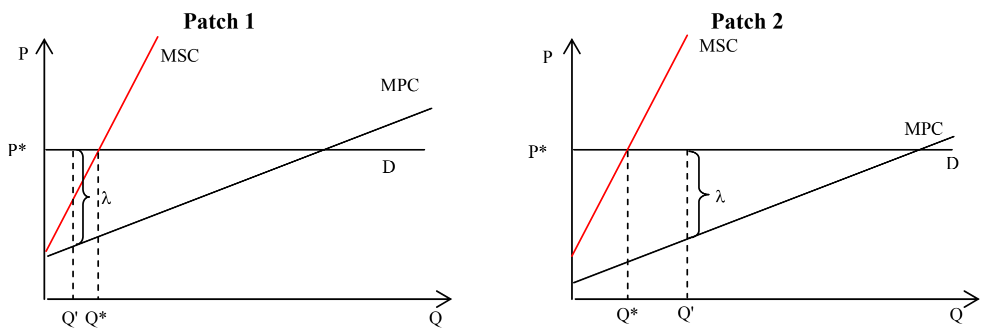


Figure 3: Quota in two heterogenous patches

4. The bioeconomic model

Marine environments are rarely homogenous in biomass and in habitat (area). There have been attempts to modify correct the homogeneity assumption in bioeconomic analysis of marine protected areas by non-homogenous areas or patches within a marine environment (Hannesson 1998, Sanchirico and Wilen 2001, Hannesson 2002, Anderson 2002 amongst others). Although these models assume homogeneity within a patch, they do allow for differences to exist between patches, and as such, partially adjust for a weak assumption.

One approach is to have different habitat areas which are interdependent and have set links between them. Meta-population analysis is used to describe the links between two or more different populations of a species. The groups are located in separate areas known as patches, and depending on the flow relationship, a movement between the patches can be described (Bulte and van Kooten 1999). Such meta-population 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 which are also linked via a certain relationship (be it dispersal or survival) (Brown and Roughgarden 1997 and Bulte and van Kooten 1999). By incorporating this method of species analysis into a bioeconomic model of a marine protected system, a better interpretation of the economic outcome can be determined.

The biological stocks in the fishery are assumed to interact under a predator prey relationship. The interaction of the two stocks takes the form as described by Ströbele and Wacker (1995) where limits to biomass are defined by carrying capacity and the level of predation. The structure takes the form:

$$(1)\quad \dot{X} = X\left[r\left(1-\frac{X}{K}\right)-aY\right] = F\left(X,Y\right)$$

$$(2)\quad \dot{Y} = sY\left(1-\frac{bY}{X}\right) = G\left(X,Y\right)$$

where
r = intrinsic growth rate of the prey population, $r > 0$;
s = intrinsic growth rate of the predators, $s > 0$;
K = carrying capacity of the prey population, $K > 0$; and
a, b = predator prey interaction parameters, $a > 0$, $b > 1$.

Without harvest, three possible equilibrium solutions exist for the biomass in such a model. Firstly, that the level of biomass of each species is zero, second that there are no predators (Y) and the biomass of the prey (X) is equal to the carrying capacity (K), and thirdly, that both species exist with the equilibrium quantities of each species obtained by setting equations (1) and (2) to zero (steady state condition) and solving the resulting equations simultaneously. The resulting equilibrium becomes:

$$(3)\quad X^{*} = \frac{rbK}{aK+rb},\quad Y^{*} = \frac{rK}{aK+rb}$$

Sub-populations of each species can occur within different patches in the ecosystem. The patches are assumed to be spatially located in the fishery and heterogenous in nature, that is, due to environmental factors, growth rates and carrying capacities of different sites differ. The biomass can move between the different patches in defined relationships. The analysis will concentrate on two types of dispersal relationships, density dependant and sink source. Without harvest, the patch level growth rates are defined as:

$$(4)\quad \dot{X}_i = F_i(X,Y) + d_{ii}^x X_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} d_{ij}^x X_j$$

$$(5)\quad \dot{Y}_i = G_i(X,Y) + d_{ii}^y Y_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} d_{ij}^y Y_j$$

where X_i and Y_i are the biomass of prey and predators in patch i respectively, $F_i(X,Y)$ and $G_i(X,Y)$ are the per capita growth rates as defined in equations (1) and (2), d_{ii} is the emigration from patch i $(d_{ii}>0)$ and d_{ij} is the dispersal rate between patches i and j (the super script on the dispersal term indicates that dispersal is species specific).The model can be used to describe n discrete patches in space each characterised by its own dynamics with linkages between all other patches.

Density dependant dispersal processes define those movements which are caused due to the relative differences in population density between the patches (Sanchirico and Wilen 2001). The simplest form of this relationship takes the form (taking the prey species as the example):

$$(6)\quad \begin{aligned} d_{11}X_1 + d_{12}X_2 &\equiv g\left(\frac{X_2}{K_2} - \frac{X_1}{K_1}\right), \text{ and} \\ d_{22}X_2 + d_{21}X_1 &\equiv g\left(\frac{X_1}{K_1} - \frac{X_2}{K_2}\right). \end{aligned}$$

where, g is a common dispersal parameter and populations flow between patches based on differences in the relative patch densities relative to the natural carrying capacities (where K_i is the carrying capacity of patch i) (Sanchirico and Wilen 2001). This trade in biomass can be seen as similar to a movement in goods from a low cost production system to a high cost (or low price to high price). Further, once equilibrium is established, these flows represent the excess supply and excess demands of the biomass densities in each individual patch.

Uni-directional flows are defined as flows from one patch to another without any reverse migration (Sanchirico and Wilen 2001). These flows are often the result of oceanographic processes such as currents, temperature, winds and others and are referred to as sink-source movements (Sanchirico and Wilen 2001). An example of a sink-source movement between two patches is as described (again using the prey species as the example:

(7) $d_{11}X_1 + d_{12}X_2 = -g\left(\frac{X_1}{K_1}\right)$

where equation (7) describes the flow from the source patch, with the flow to the sink patch described as (8):

(8) $d_{22}X_2 + d_{21}X_2 = +g\left(\frac{X_1}{K_1}\right)$

In this kind of flow system, biomass continues to flow between patches once equilibrium has been established (Sanchirico and Wilen 2001).

A further assumption in the model is that there are no deaths or predation on individuals whilst they migrate from one patch to the other. Under a two patch situation, the biological system can be described as shown in Figure 4. As the two patches are linked via the dispersal relationships, any changes that occur within one patch will influence outcomes in the other. Under a harvest situation, a change in access rights of fishers to either patch can yield different outcomes. Whether or not these outcomes yield positive benefits to all stakeholders (fishers, conservationists and society) will depend on the choice of patch to become a marine protected area.

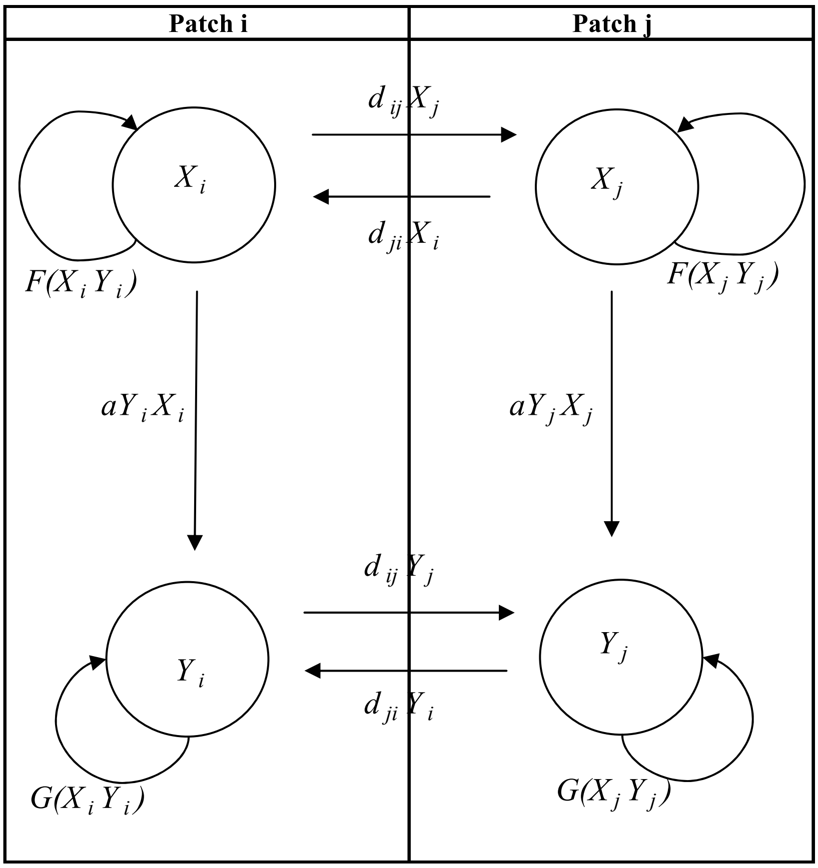


Figure 4: The biological system

A closed biological system is not considered in this analysis. In a multi-patch fishery, where all patches are separate, that is, there are no linkages between them; the closure of a patch as a marine park which previously was used for fishing will decrease catch. As effort (if not reduced) is confined to a smaller area, individual fishers rents will be reduced, thus seeing a fall in payoffs for fishers. Despite this, total biomass will increase in the closed patch but may fall in the other patches as effort will be increased. This has been shown by Sanchirico and Wilen (2001) for a single homogenous species.

For the purpose of this paper a two patch system will be analysed. Two patches allow for a simplified analysis whilst creating a situation where general results can be obtained which apply to a greater number of patches.

4.1 The exploiting industry

In the initial instance, fishing occurs in both patches where the unit cost of effort differs for each species. The two patches will be assumed to be of different biological character with different carrying capacities. Patch 2 is assumed to have a greater carrying capacity due to superior habitat.

Fishing is allowed to move freely across patches such that fishers respond to changes in rent in different patches at some response rate (u). The fishery is initially managed under a situation where fishers who operate in the fishery are required to pay a tax per unit of effort. This control means that the total amount of effort is limited in the fishery.

The predator species is assumed to be of greater commercial value and hence targeted by fishers. The prey species is also of commercial value, except the returns are much lower. In many fisheries, particularly those in NSW, fishers are multi-endorsed. Thus, the total effort applied to the fishing business is a function of total rents. Fishers will apportion effort such that the marginal value of effort from fishing the predator species is equal to the marginal value from the prey species. In this way, fishers operate rationally so as to maximise their profits from the fishing activities.

The total revenue (TR) from fishing activities is defined as the sum of total revenue from harvest, that is price (P_x, P_y) multiplied by harvest for each species. Further, it is assumed that $P_x < P_y$ so as to represent the higher commercial value of the predator catch. Fishers are assumed to be price takers due to competition from different fisheries so that the prices received are not influenced by an individual's catch and because there is a large number of fishers. The unit cost of effort is assumed to be constant, so that the total cost from the fishing operation becomes $TC = c{\cdot}E^x + c{\cdot}E^y$.

As discussed, effort across the different patches adjusts to differences in rent at a speed u. For each individual patch, effort adjusts so that long run rents in all patches are equal. However, as the fishery operates under limited entry, an upper bound on the level of effort exists due to the imposed community contribution. The rents generated are simply the total revenue from fishing less the total cost of fishing including opportunity costs (ψ):

(9) $R(E,X) = P_x \cdot H(E,X) - c \cdot E_x - \psi E_x,\ R(E,Y) = P_y \cdot H(E,Y) - c \cdot E_y - \psi E_y$

The exploiting industry is assumed to operate under a Schafer production function (Schafer 1957). The harvest function is $H_i(E,J) = q^j{}_i E^j{}_i J_i$ where $q^j{}_i$ is the catchability of species j in patch i, $E^j{}_i$ is the effort applied to catch species j in patch i and J_i is the biomass of species J (that is, prey or predator) in patch i. In the case of the model presented in this paper, there are two species, the prey species (X) and the predator species (Y).

In the situation where an open access institutional structure exists, all rents are dissipated. As the rent function is linear in effort, the rent function can be re-written such that $R(E,X) = R(X)E$. Since effort is positive when fishing occurs, the function $R(X)$ must equal zero for rents to equal zero. As such, the open access level of biomass can be derived using the approach set out in Sanchirico and Wilen (2001) bu setting the rent equation to zero:

$$(10)\quad X_i = \frac{(c+\psi)}{P_x q_i^x}$$

However, when the fishery is managed under a limited entry situation, controls are in place to limit the amount of rent captured in the fishery, as a result the fishery has positive rents. The relation above needs to be modified in order to capture the extra rents, such that:

$$(11)\quad X_i = \frac{R(X_i)+(c+\psi)}{P_x q_i^x}$$

where it can be seen when rents are positive, the equilibrium level of biomass will be greater than under open access. Under limited entry, fishers are required to make a community contribution as payment for access to the resource. The community contribution is such that it is paid on the level of effort a fisher invests in the fishery, that is, a user pays charge on access. The contribution per unit of effort (equivalently it could be a quota price per unit of effort or a license fee for access to the resource) is defined as ρ, such that ρ will be equal to $R(X_i)$ in equation (11). In this way, fishers will equate their profits to zero as under open access to determine their optimal level of effort in the fishery.

Equation (11) provides an exploited equilibrium for any given level of resource rent or community contribution. In order to determine the level of resource rent under limited entry the institutional structure that provides for the management of the fishery imposes a community contribution (which is equivalent to enforcing a given level of resource rent). The flexibility of this approach is that the level of effort or quota reduction required to maintain current rents in the fishery can be determined.

Several institutional structures will be examined via the bioeconomic model. First, a structure where the prey stock are subject to management controls (limited entry) will be examined, second when the predator stock are subject to limited entry, and thirdly, when both stocks are subject to limited entry. The impact of a marine park being established in one patch will be examined in order to find the conditions necessary to provide a win-win outcome for both types of stakeholders (fishers and conservationists).

4.2 Density dependant dispersal

A density dependant dispersal process will be first used to examine the effects of creating a marine park in one of the patches. Under this dispersal process, biomass will move from one patch to the other depending on relative population densities. Once a marine park is created, the biomass in that area will increase, creating a change in relative densities. Biomass will then move out of the protected area into the exploited patch, creating a positive externality for fishers who operate in that patch. It is the magnitude of this externality which will characterise the 'win' for fishers. The initial exploited bioeconomic model for prey and predators in patch *i* is shown in equations (12) and (13) respectively:

$$(12)\ \dot{X}_i = X_i\left[r\left(1-\frac{X_i}{K_i}\right)-aY_i\right]+g^x\left(\frac{X_j}{K_j}-\frac{X_i}{K_i}\right)-q_i^xE_i^xX_i$$

$$(13)\ \dot{Y}_i = Y_i\left[s\left(1-\frac{bY_i}{X_i}\right)\right]+g^y\left(\frac{bY_j}{X_j}-\frac{bY_i}{X_i}\right)-q_i^yE_i^yY_i$$

The equilibrium effort and harvest (denoted by the last term in equations (12) and (13)) will be found by determining the steady states for equations (12) and (13). By setting the change in prey biomass and change in predator biomass equal to zero, the steady state effort and harvest are found and presented in Table 2.

Table 2: Effort and harvest under density dependant dispersal

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

4.3 Sink-source dispersal

A sink-source dispersal relation describes a uni-directional move of biomass from one patch to the other. A simplified version of a sink-source flow is described by Sanchirico and Wilen (2001) and is given in equations (7) and (8). Under such a dispersal pattern, the growth rates in patch *i* for both the prey and predator species are given by:

$$(14)\ \dot{X}_i = X_i\left[r\left(1-\frac{X_i}{K_i}\right)-aY_i\right]-g^x\frac{X_i}{K_i}-q_i^xE_i^xX_i$$

(15) $\dot{X}_i = X_j\left[r\left(1-\frac{X_j}{K_j}\right)-aY_j\right]+g^x\frac{X_i}{K_i}-q_j^xE_j^xX_j$

(16) $\dot{Y}_i = sY_i\left(1-\frac{bY_i}{X_i}\right)-g^y\frac{bY_i}{X_i}-q_i^yE_i^yY_i$

(17) $\dot{Y}_j = sY_j\left(1-\frac{bY_j}{X_j}\right)+g^y\frac{bY_i}{X_i}-q_j^yE_j^yY_j$

Equations (14) and (15) describe the flow of prey biomass between the source patch (14) and the sink patch (15). Again, it is clear that no predation or deaths are assumed to occur during the movements between the two patches. As for the prey species, the same dispersal is assumed to occur between the patches as in the predator species. Equation (16) describes the change in biomass in the source patch with equation (17) describing the sink patch.

Table 3: Effort and Harvest under sink source dispersal

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

The exploited equilibrium levels of effort and harvest are described in Table 3. These equilibrium levels are found by setting the change in biomass in each patch equal to zero, and subsequently solving for effort and harvest.

5. Results from the model

The different institutional structures examined may govern whether or not a marine park can create economic benefits with or without further intervention in the fishery. As policy makers impose a desired resource rent requirement, exit from the fishery will occur due to the establishment of a marine park in one of the patches if it causes effort to decline. In practice, this effort may need to be 'purchased' by the managing institution. This situation can be seen as analogous to a closure in a quota managed fishery which subsequently leads to a reduction in the total allowable catch of a particular species. From the model result, it will be possible to see what level of reduction in catch is necessary to maintain the current level of resource rents.

The results from each of the three scenarios are discussed in the following sections. Under density dependant dispersal flows, the choice of which patch to close if of equal size and biological character, is arbitrary (it is similar to the case of one homogenous biomass), however when the patches are of different biological character choice of the patch is important. In the sink-source case, as the biological character of the patches is different due to the dispersal relation, the choice of patch will always be important in describing the outcome. As such, for density dependent the patches are believed to be of different biological character, with Patch 2 (the one which is closed) of greater carrying capacity. The parameters used for the comparative statistics results are based on numbers used by other authors using such a procedure (for example Conrad 1999, p.48).

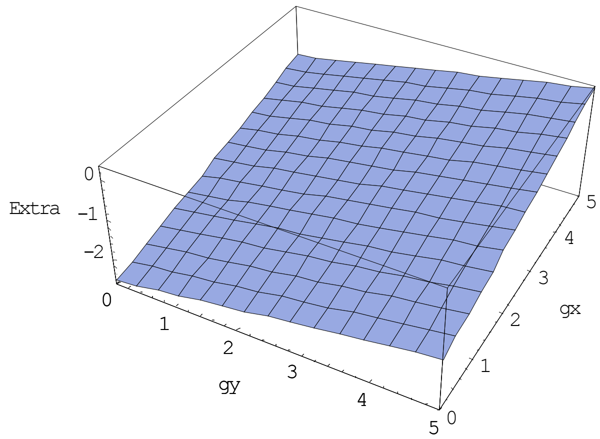
Once a patch is closed, biomass of predators and prey will increase to the non-harvest equilibrium. Equilibrium biomass for predators and prey is defined by equation (3). The equilibrium biomass under a marine park is larger than that under the exploited equilibrium. The establishment of a protected area thus results in an aggregate increase in biomass if the economic conditions in the exploited patch remain the same post establishment.

5.1 Scenario 1: Limited entry prey, open access predator

Assuming economic conditions remain the same and harvest occurred in both patches prior to establishing a marine protected area, biomass will increase. Harvest will only increase under certain conditions. The solution is dependent on twenty different parameters. As such, analysis of the full range of combinations (a total of 172) is not possible here. Instead, general conditions that give rise to a positive increase in harvest post the establishment of a marine protected area will be discussed.

The dispersal rates of biomass between patches will have a positive effect on the possibility of a double gain. The feasible region for a double gain under certain assumptions can be seen in Figure 5 where w_i and m_i are exploited equilibrium biomass of prey and predators in patch i respectively. It can be seen that an increase in harvest as a result of the establishment of a marine protected area is positively related to both dispersal rates. The possibility for a double gain is further enhanced by a high flow of prey stock, whilst the effect of flows of predators is not as significant. A high dispersal rate of prey increases flow from the marine protected area to the fishing ground, as such it simultaneously has a positive effect on both prey and predator catch (through increased carrying capacity for predators in the fishing ground). However, the flow for predator given prey dispersal has a much smaller effect as it only influences predator catch.

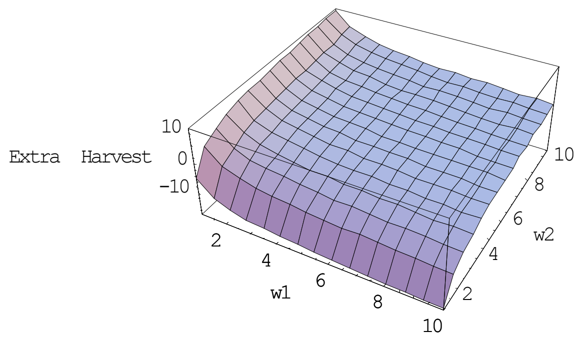
The level of exploitation in the patches prior to the zoning of a marine protected area will influence the ability to realise a double gain. If a patch is highly exploited, then there will be a significant increase in biomass as a result of the new protected area, however, it will mean a large reduction in catch reducing the possibility of a double gain. Post the establishment of a protected area, low levels of exploited biomass in Patch 2 (the patch that is closed), will lead to decreased harvest for any level of biomass in Patch 1 (Figure 6). The reason for this is the significant reductions in harvest as a result of closing a patch where the costs of fishing (or price received for fish) are relatively low (higher).



where r= 0.8, s = 0.2, a = 0.02, b = 2, f = 5.27, t= 10.43, w1=5.55, w2=5.35, m1=2.38, m2=2.38, K1 = 12, and K2 = 14.

Figure 5: Harvest response to dispersal

Further, it can be seen that for high levels of exploited biomass in Patch 2, the possibility of an increase in overall harvest is greater. The reason that this occurs is that at high levels of exploited biomass in Patch 2, there would have been little harvest due to relatively higher costs (or lower prices received for fish). Thus, the closure of a high cost patch yields little effect on total harvest as the flow from the high cost patch to the low cost patch creates additional benefits. This is emphasised by the ridge in Figure 6 for low values of biomass in Patch 1.

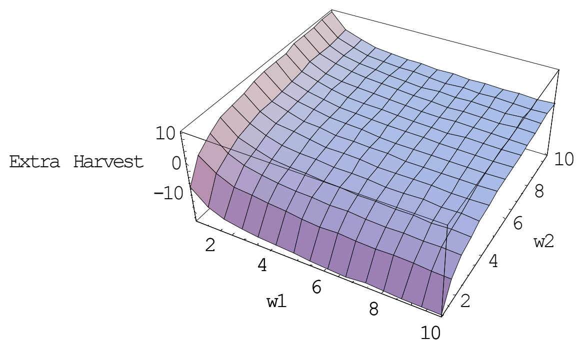


where r= 0.8, s = 0.2, a = 0.02, b = 2,f = 5.27, t= 10.43, m1=2.38, m2=2.38, qx = 0.01, qy = 0.06, K1 = 12, and K2 = 14.

Figure 6: Harvest response to exploited prey biomass

As the level of biomass of prey species determines the carrying capacity for the predator stock, the possibility for increased harvest of predators will be determined by the change in prey biomass. Given differing levels of exploited prey biomass, the change in predator harvest is shown in Figure 7. As for the change in total harvest, the predator harvest response is similar. The reason that the same relationship holds is due to the link between predator biomass and prey biomass, in the model predator biomass can never exceed prey biomass divided the parameter *b*.

In order to determine whether total effort would be reduced in the fishery, change in effort was evaluated against the level of community contribution (resource rent). It can be seen that a positive community contribution can have a positive effect on effort post the establishment of a marine park (Figure 8a). This is apparent since under a system of community contribution, the cost of fishing is higher and as such the exploited equilibrium of biomass is also higher (equation 15). As the creation of the marine reserve creates a further increase in biomass in the exploited patch, fishers expend greater effort to catch the fish, and as no limits to predator catch are currently in place, the increased biomass of prey increases the carrying capacity of predators and thus the level of harvest and effort expended to catch this species.

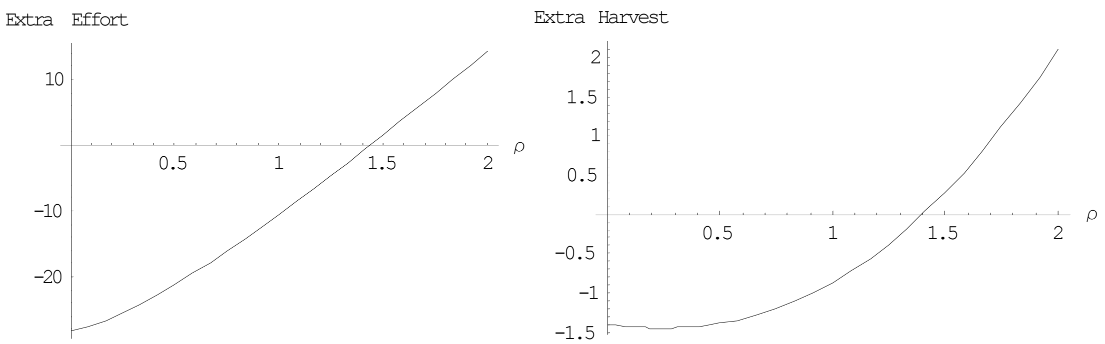


where r= 0.8, s = 0.2, a = 0.02, b = 2,f = 5.27, t= 10.43, m1=2.38, m2=2.38, qx = 0.01, qy = 0.06, K1 = 12, and K2 = 14.

Figure 7: Harvest of predators response to exploited prey biomass

The increase in effort as a result of a certain level of community contribution means that the governing institutional structure may actually benefit from the creation of a no take zone. This, if combined with a gain for fishers (through increased harvest) and conservationists (through increased biomass) there is the possibility for a net gain for all stakeholders.

(a) Effort (b) Harvest



where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 14, gx =2, and gy = 2

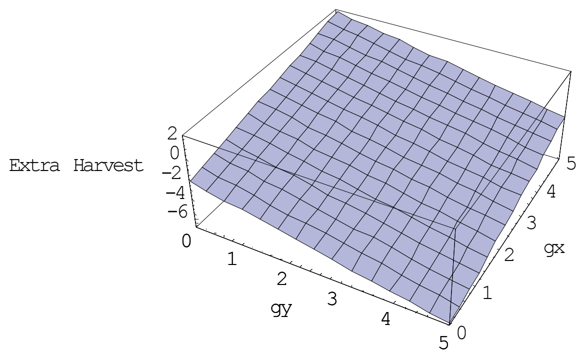
Figure 8: Effort and harvest response to community contribution (prey)

Further to the impact on effort, a similar relation to the level of harvest exists. Given certain levels of community contribution, the level of harvest will actually increase *ceteris paribus* as a result of the establishment of a marine protected area (Figure 8b). The shape of this relation is due to the same influences that lead to increased effort.

Under a sink source dispersal relationship the choice of patch will determine whether or not an increase in harvest and biomass is possible. With a single stock, Sanchirico and Wilen (2001) observed that a closure in the sink patch will not increase harvest under any biological or economic condition, but will however, lead to an increase in biomass. This result holds under a predator prey metapopulation model. It can be seen from Table 3, that the equilibrium harvest and effort equations for the source patch do not include values for the biomass in the sink patch. This is due to the uni-directional nature of the biological flow (there is no flow from the sink to the source) and as such, a closure will only increase biomass in the sink patch.

Despite this, it is possible for a double gain to be realised given a closure of the source patch. The closure of the source patch leads to an increase in the dispersal flow, and thus creates a positive externality from the marine protected area. Depending whether the exploitation of this externality is greater than the cost of forgone harvest in the protected area, there is a possibility for a double gain.

The impact of dispersal rates on the possibility for there to be a double gain as a result of the creation of a marine protected area is positively related to dispersal rates for prey, but negatively related to those of predators (Figure 9). The cause of this is due to the link between predators and prey in terms of carrying capacity. High rates of prey dispersal increases the positive externality created from the protected area and also increases the carrying capacity of predators. A high predator dispersal rate will increase predator harvest but will place extra pressure on prey stocks.



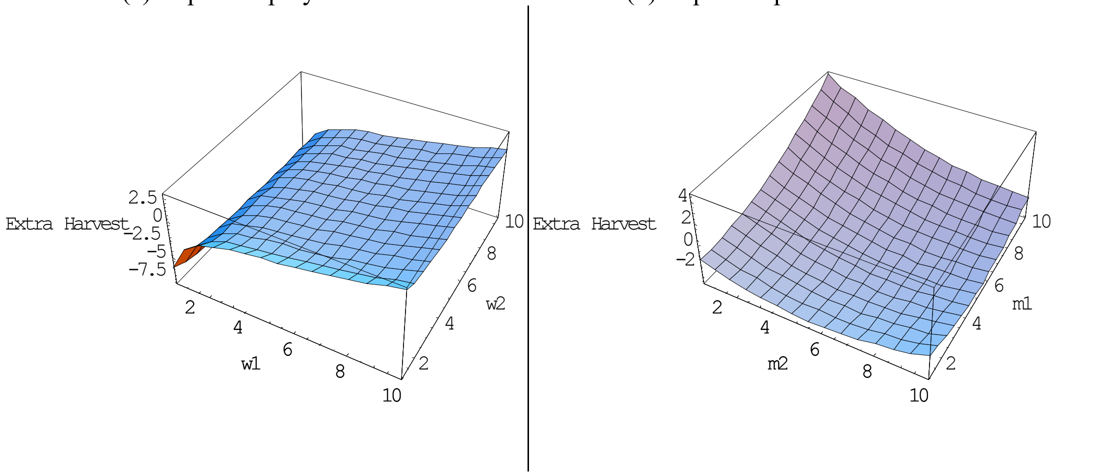
where r= 0.8, s = 0.2, a = 0.02, b = 2,f = 5.27, t= 10.43, m1=2.38, m2=2.38, w1=5.35, w2=5.35, K1 = 12, and K2 = 12.

Figure 9: Sink Source harvest response to dispersal rates (prey)

The result obtained for dispersal rates suggest that under a harvest system for two competing stocks, it is better to choose a patch with high dispersal for prey, but relatively low dispersal of predators. This is contrary to the density dependant case where the benefits to a marine protected area increased as a result of high dispersal rates for both species.

The pre-reserve level of exploitation will impact on the possibility of a double gain from the closure of one patch. Under a sink source dispersal relationship, the possibility of gaining increased harvest post the establishment of a marine protected area is positively related to both level of exploited prey biomass in either patch (Figure 10a). To realise a double gain, the source patch needs to be closed (Patch 1). It can be seen that high levels of biomass in Patch 1, lead to a double gain as the opportunity cost of closing this patch is low. This infers that the closure of a high cost source patch will increase the chance of a double gain. The effect of the biomass in the exploited patch is only small, with the effect of the source patch dominating the outcome (Figure 10a). The result for increased predator catch follows the relation shown in Figure 10a.

(a) Exploited prey biomass (b) Exploited predator biomass



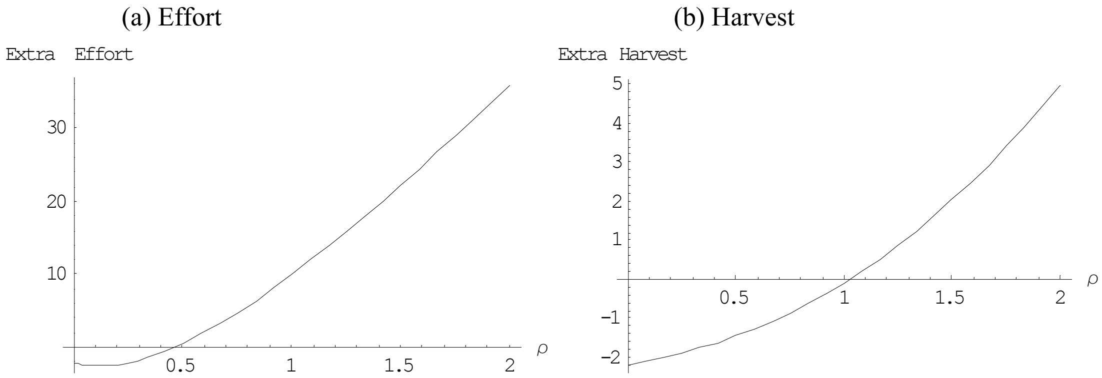
where r= 0.8, s = 0.2, a = 0.02, b = 2,f = 5.27, t= 10.43, m1=2.38 (a), m2=2.38 (a), w1= 5.31 (b), w2 = 5.31 (b) qx = 0.01, qy = 0.06, K1 = 12, and K2 = 12.

Figure 10: Sink Source harvest response to exploited prey and predator biomass (prey)

The result obtained for the effect of exploited predator biomass on the outcome of a double gain is somewhat ambiguous. High levels and low levels of biomass in the sink and source patch increase the possibility for a double gain (Figure 10b). High levels suggest that the costs of harvest are relatively high, with low costs suggesting the opposite. However, harvest increases greatest when the exploited levels of biomass in Patch 1 (source) are high, and exploited biomass in Patch 2 (sink) are low. This follows from the arguments presented for exploited prey biomass levels.

The response of effort to the level of community contribution under a sink source dispersal relationship indicates that at certain levels, effort expended in the fishery will actually increase as a result of the creation of a marine protected area (Figure 11a). As the level of contribution increases the exploited biomass, it creates the opportunity for increased effort as fishers respond to catch the fish that flow from the source patch. If the contribution is such that the level of effort forgone in the closed patch is only small, then total effort will increase. The results suggest that the closer to open access, more effort will be required to be removed from the fishery. The result is maintained when only a single biomass is harvested under a limited entry fishery (Sanchirico and Wilen 2000).

The result obtained for effort is also seen in terms of increased harvest. There is a positive relation between the levels of community contribution and harvest; however the point where it becomes positive is greater than that seen for effort (Figure 11b). This suggests that whilst there may be no reduction in effort in the fishery as a result of the creation of a marine protected area, harvest may fall leading to a possibility of decreased returns to fishers.

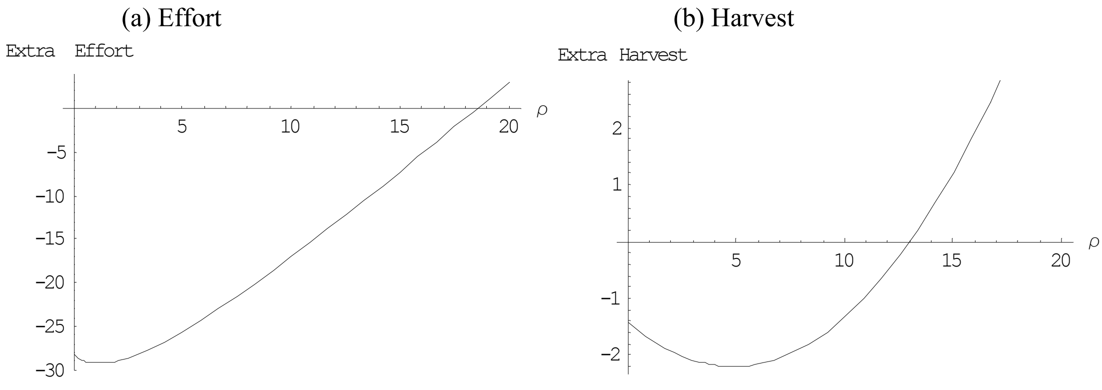


where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 12, gx =2, and gy = 2

Figure 11: Sink Source effort and harvest response to community contribution (prey)

5.2 Scenario 2: Limited entry predator, open access prey

Under a density dependant disposal flow system, results for a double gain are similar to those under limited entry for prey. The influence of both dispersal rates and initial levels of biomass are the same, as the underlying reasons for those outcomes remain unchanged given a community contribution. Despite this, the influence the level of community contribution has on the level of effort differs from that seen under a controlled prey situation. For certain values of community contribution, the change in level of effort (Figure 12a) and harvest (12b) as a result of the establishment of a marine protected area is negative. For large values of community contribution there is a positive change in effort and harvest with the curves generally experiencing a positive slope.



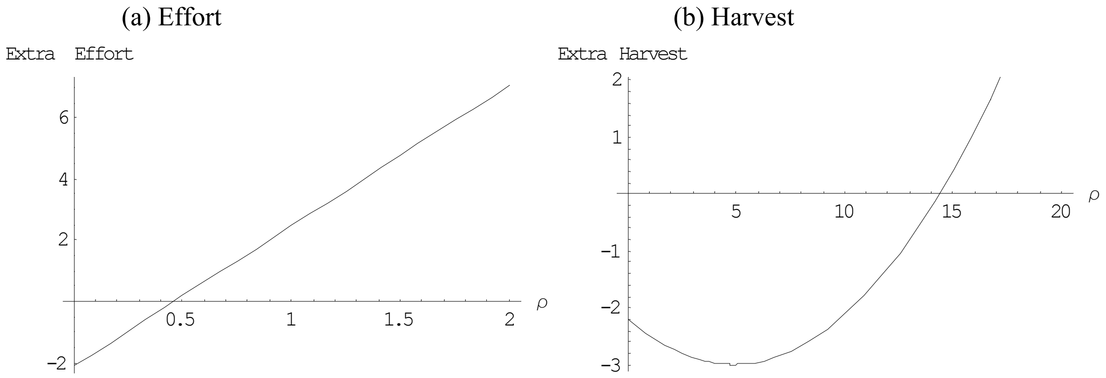
where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 14, gx =2, and gy = 2

Figure 12: Effort and harvest response to community contribution (predator)

The values of community contribution for which a positive effect on harvest and effort occurs are such that the cost of fishing would be prohibitive. These results show that with the given vales for the remaining parameters, the influence on harvest and effort as a result of the creation of a marine protected area would be negative. As such, if effort was limited in the fishery, a buy back scheme or some other effort retirement scheme would be required in order to maintain the desired level of resource rent from the fishery.

Despite this negative effect, the curves shown in Figure 12a and 12b shift up given higher costs of harvest for the prey species. The cause of this is that given higher costs of harvest for prey, there will result a greater exploited equilibrium biomass, and thus a greater carrying capacity for predators.

The impact of dispersal rates and the initial exploited levels of biomass under a sink source dispersal flow when a marine protected are is established in the source patch are similar to those under a prey controlled structure. Similarly, to gain increased effort in the fishery or to maintain effort, relatively low levels of community contribution are required (Figure 13a). However, for harvest to increase, prohibitive levels of contribution are required (Figure 13b).



where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 12, gx =2, and gy = 2

Figure 13: Sink Source effort and harvest response to community contribution (predator)

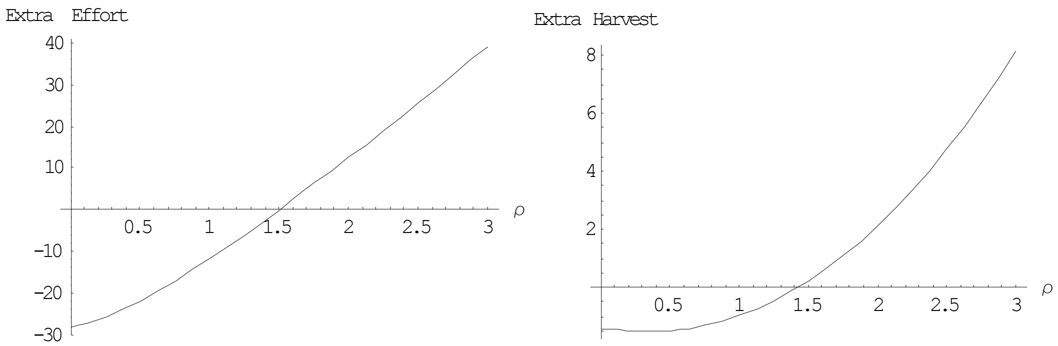
As a result of the creation of a marine protected area when predator stocks are subject to managerial controls which either limit effort of catch, the post establishment level of harvest will fall. This will occur despite in some cases an increase in effort indicating that some fishers' economic viability may be impacted as a result.

5.3 Scenario 3: Limited entry

The results for increased harvest under a density dependant dispersal where the harvest of both species is conducted under some managerial controls are similar to those obtained for Scenarios 1 and 2. However, the influence of biological and economic factors related to the predator stock is more significant than under the first two scenarios. The influence of community contribution to the possibility of a double gain follows more closely the outcome achieved under scenario 1. When both species are managed under a system of community contribution, it is possible for there to exist a situation where effort (Figure 14a) and harvest (Figure 14b) increased post the creation of a marine protected area.

The cause of the increased harvest and effort is a result of the creation of a marine protected area is once again related to the level of prey biomass. As prey biomass is greater than under open access conditions, it increased both the possibility of extra harvest for prey and predators after re-zoning one patch.

(a) Effort (b) Harvest



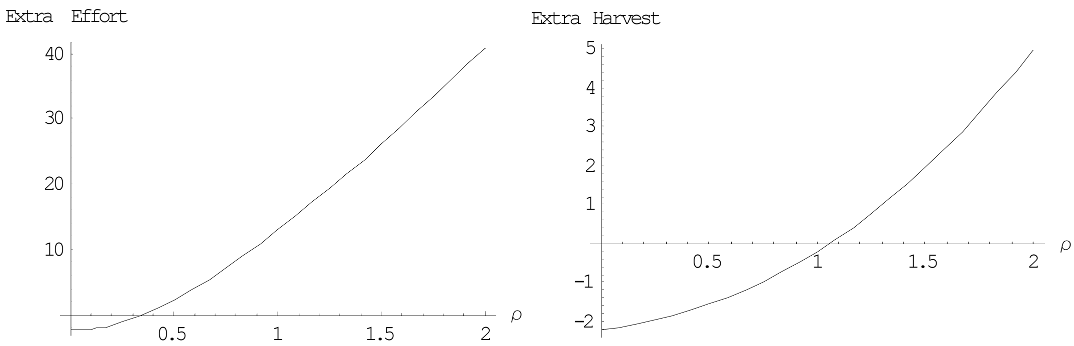
where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 14, gx =2, and gy = 2

Figure 14: Effort and harvest response to community contribution (both species)

As with the results obtained for the density dependant dispersal relation, under a sink source dispersal system, the closure of the source patch (Patch 1) leads to an outcome which is dominated by the prey response. However, an increase in effort as a result of the creation of the protected area occurs at a much lower level of community contribution than seen for either the prey of predator controlled scenarios (Figure 15a). Only small levels of community contributions are required to yield a positive level of effort post establishment. This indicates that the establishment of a marine protected area in a limited entry fishery may not require further regulation or actions by the management authority.

Despite an increase in effort occurring at low levels of community contribution, increases in harvest occur at higher levels of community contributions (Figure 15b). This result indicates that at some levels, fishers may exist from the fishery despite the possibility of increased effort due to pressure on their economic viability.

(a) Effort (b) Harvest



where r= 0.8, s = 0.2, a = 0.02, cy = 3.5, cx = 1, py = 25, px = 20, ψ = 0.07, qx = 0.01, qy = 0.06, b = 2, K1 = 12, K2 = 12, gx =2, and gy = 2

Figure 15: Sink Source effort and harvest response to community contribution (both species)

6. Policy implications

The analysis shows that the creation of a marine protected area will not necessarily adversely affect fishers. Depending on the biological system, processes that result due to the creation of the protected area will maintain or even increase catch and effort. This means that buybacks or further restrictions on effort may not be required when fisheries managers are using marine parks to manage stocks.

Further, it was shown that at certain levels of restricted effort, harvests and effort may increase. The increase in effort would then (under the system of a tax on effort) increase the returns to society, through increased revenues from the community contribution. This also indicates that under a system of effort or quota control, the resource rents from the stocks in the fishery would increase. This increase can be viewed as a gain to society and suggests that marine parks coupled with certain other efficient management structures may create a situation where all stakeholders are better off.

The management of fish that interact under a predator prey structure is seen to be most effective if the management controls concentrate on the prey stock. In the model, a relationship was used such that the carrying capacity of predators was related to the biomass level of prey. As such, with restrictions on prey, the carrying capacity for predators is increased, allowing them to become more abundant. Further, with the creation of a marine protected area where no fishing activities are allowed to take place, the possibility of fishing the predators to extinction of very low levels is reduced due to the export of stock from the protected area (depending on the dispersal relationship).

The analysis conducted showed via comparative statistics that an economic justification for the use of marine protected areas as a fisheries management instruments can be found. The increased in resource rents showed that marine protected areas can be used in order to manage the resource in an more efficient manner than under open access. The benefit of the use of marine protected areas over other efficient controls (that is those controls which do not create the incentive for fishers to increase the use of inputs above an efficient level) is its management simplicity. Further, if under a limited entry (or controlled fishery) institutional structure, as long as fishers were able to redistribute effort away from the protected area grounds in an efficient manner, there is a possibility that fishers will not be worse off.

The creation of a marine protected area may mean that some fishers will leave the industry. If the protected area creates the situation where for some fishers the cost of accessing the new/alternate fishing grounds is prohibitively expensive, then it will means they will leave the industry. However, the external benefit created by the protected area will mean that other fishers will become more viable and wish to increase effort. This situation (if a trade in effort or quota existed), would create the incentive for the fishers that benefit to purchase quota or effort from fishers that were adversely effected. In this way, a benefit transfer should be created such that all parties are at least as well off. However, if this were not available, a buyback or other compensation scheme may be necessary in order for all parties to benefit.

7. Concluding comments

The bioeconomic analysis indicates that the use of marine protected areas as a fisheries management strategy may lead to benefits for all stakeholders. This outcome is dependant on the biological characteristics of the biomes to be re-zoned. Different dispersal structures may provide benefits to fishers are they exploit the positive externality that is created from the protected area. This positive externality describes the net gain to fishers as a result of the closure of a certain area. As the closure of an area increases biomass, a conservation outcome was assumed to be satisfied. Further to this, to find the optimal allocation the values associated to biodiversity, non-use and alternate uses of the area (such as recreation) should be incorporated in order to determine the efficient size of a protected area.

It was seen that current management structures imposed on the fishery had influence on the possibility of a payoff to both fishers and conservationists. This suggests that certain structures would enhance the opportunity for marine parks to create value for fishers, whilst other controls may hamper or prevent this value creation. A reason as to why a marine protected area may lead to greater benefits under existing fisheries control in linked to investment. Marine resources can be viewed as natural capital that can be invested in or used to generate a return for its owner (Carter 2003). Investment traditionally refers to the sacrifice in present consumption in order to expand man made capital so that future consumption can also be increased. Natural capital, is however, not man made and cannot be man made. Despite this, natural capital is analogous to man made capital in its function. Capital can be redefined as a stock that yields a flow of useful goods or services into the future (Daly 1994). When investing in renewable natural capital (renewable resources can be exploited and hence become non-renewable), the investment decision or 'waiting' means the constraining of annual offtake (Daly 1994).

Some avenues for further work are discussed here. The analysis conducted was under a deterministic context. The further the outcomes, a stochastic component could be added to the model with random stochastic shocks. This process would further the analysis to include outcomes where a marine protected area may decrease the variance in catch, or make a system more 'robust'. Conrad (1999) examined a bioeconomic model of a marine protected area for a single homogenous biomass which occurred in two separate patches. It was seen from the simulations that as the size of the reserve increased the ability for it to lower the variance in stock levels within the fishing grounds increased.

Boersma and Parrish (1999) argue that theoretically, the establishment of a no-take area would lead to population growth to increase via a decrease in adult mortality and through increases in female fecundity as a result of the change in population structure. This effect may then additionally insulate the population against external shocks and environmental extremes. In order to model such a relation, a separation of stocks into adults and juveniles could be conducted. This separation would also allow an analysis of certain gear controls and other catch controls based on the age of the fish (analogous to size). This separation would be sufficient to evaluate changes in biomass caused as a result of the establishment of a marine protected area.

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