Quotas, Marine Reserves and fishing the line:

When does Marine Reserve Creation Pay?

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Abstract

This paper explores the issue of using marine reserves in combination with quotas as fisheries management tools using a patchy environment model as the biological foundation. The rent generated by fishing on the total population, using optimal quotas as a management tool, is compared to the rent from the fishery when managed with quotas and a marine reserve. This is done under different assumptions regarding the type of dispersal mechanisms between the sub-populations in the different patches and under two different assumptions regarding the harvest function. It is shown that the profitability of reserve creation depends on the migration rate relative to the intrinsic growth rate and the cost / price ratio and that the choice of harvesting function is of particular importance when the costs of fishing are high.

KEY WORDS: fishing the line, marine reserves, metapopulation models, optimal quotas.

JEL classification: Q22

INTRODUCTION

Marine reserves are zones in the marine habitat in which fishing is prohibited for certain parts of the time, or at all times. As conventional fisheries management has been shown to suffer obvious shortcomings such as cheating, high management costs and bycatch problems (for instance, Guénette et al. 1998), attention has been drawn towards alternative methods of management, marine reserves being one of them (see Sumaila 1998a and Conover, et al. 2000). Reserves may have several potential benefits (see for instance Bohnsack 1993, and Roberts & Polunin 1993); protection of spawning biomass, provision of recrutment sources for the surrounding areas, supplemental restocking of fished areas through emigration, maintenance of natural population age structure and sex ratio, maintenance of undisturbed habitats and insurance against management failures in fished areas. Conservation biologists have been enthusiastic about reserves, but the question whether marine reserves may enhance fisheries or not is still much disputed as empirical evidence is scarce. A few studies that do not contradict the theory do however exist (McClanahan & Kaunda-Arara 1996, Russ & Alcala 1996, Roberts et al. 2001).

Some theoretical bioeconomic studies have been made on the effectiveness of marine reserves. Hannesson (1998) found that a reserve combined with open access would result in a lower stock size, lower catches and a higher exploitation rate than optimal quotas for all relevant sizes of reserves and migration rates. Armstrong and Reithe (2001) found that these results are modified if management costs are included in the calculations. Both Sumaila (1998b) and Conrad (1999) compared the use of optimally set quotas only, to marine reserves in combination with quotas, finding that in a deterministic setting, optimally set quotas alone is the rent maximizing strategy. In all of the work mentioned above, it is assumed that the fish is homogeneously distributed over an area. It is further assumed that the reserve may be of size 0 to 100 % of this area, measured on a continuo scale, and that the sub-stocks and their growth will be proportional to the size of the area they live in.

Sanchirico & Wilen (2001) also compare solely open access to a marine reserve combined with open access, but as opposed to the above-mentioned studies their work includes the spatial dimension is included both in the biological and economic part of the model. In this type of model the management unit is the metapopulation, which is assumed to consist of a group of linked sub-populations distributed across a set of spatially discreet habitats or patches. The reserve consists of the patches of one or more sub-stocks. Each sub-stock has its own population dynamics, but some or all are connected though different dispersal mechanisms. Sanchirico & Wilen (2001) show that when patches are linked through unidirectional flow of individuals (sink source system) or density dependent migration, reserve creation may increase stock and harvest if the cost / price ratio is low and for given values of the intrinsic growth rate / migration rate ratio. Brown and Roughgarden (1997) use a metapopulation model to find optimal management of barnacles. The barnacle has a two-stage life cycle, the first lived in a common oceanic larval pool, the second at a local coastal site. They show that the optimal strategy, in terms of maximizing discounted net benefits, is to harvest on one patch only, setting the other patches off as nurseries or reserves. Hence, it seems as if reserves may have the greatest potential as a rent maximizing strategy in the management of species whose population dynamics may be described with metapopulation models.

In the following, the biological part of the type of metapopulation model applied by Sanchirico & Wilen (2001) will be used to compare the per period equilibrium rent of a fishery managed by the use of quotas solely and quotas in combination with a reserve. The economic part of the model is however formulated differently as other issues are addressed here. Hence, this work differ from previous theoretical bioeconomic studies of marine reserves in that a metapopulation model applied in the analyses of reserves combined with optimal quotas. It also differs in that two different harvest functions are considered under the reserve regime; in the first scenario a standard Schaefer catch function, in the second a new harvesting function meant to mimic the situation where much of the fishing occurs at or near the boarder of the reserve (a situation often referred to as "fishing the line").

Several studies reports that fishing the line is a common practice in fisheries where manrine reserves are implemented. For example, satellite transponders on boats in the New England scallop fisheries have shown vessel tracks clustered close to the boarders of areas that are closed to ground fish trawling (Morawski, 2000). Bohnsack and Ault (2002) reports that in the fishery for lobster outside the Sambos Ecological Reserve in the Florida Keys fishermen prefer to put the traps close to the boarder of the reserve. Shorthouse (1990) interviewed fishermen trawling in the area close to the Great Barrier Reef Park in Australia and they reported increased catches from fishing the line. It may therefore be reasonable to assume that the catch per unit effort (CPUE) could be higher near the boarder when there is a net flow of fish from the reserve, than would otherwise be the case. Hence, fishing the line may be an important factor when estimating the profitability of reserves in terms of rent from fisheries and an attempt to model this type of behavior is made in this paper. The results from using the "fishing the line" function and a standard Schaefer catch function are then compared. In order to keep the modeling framework simple, benefits from the fishery are restricted to account for any rent generated.

The analysis is conducted under two different assumptions regarding migration; a sink-source system and a system with density dependent migration. It is shown that in the sink-source case the profitability of reserve creation depends on the migration rate relative to the intrinsic growth rate and the cost / price ratio. Furthermore, the higher the costs and the higher the intrinsic growth rate the wider the range of migration rates that allows for profitable implementations of reserves. In the case where the patches were assumed to be linked through density dependent migration the profitability of a reserve depends on the rate of migration back to the reserve, the migration from the reserve relative to the intrinsic growth rate in the reserve and the level of costs. For a given set of assumptions regarding the biology it is shown that the rent of the reserve case is lower when the Schaefer harvest function is used than for the alternative catch function.

The next part will introduce the general modeling framework and is followed by results from applying the model to the two-patch case under quota and quota combined with a reserve regimes and various assumptions regarding migration and harvest functions. Finally a summary and some concluding remarks are given.

THE MODEL

The biology

This section provides a brief presentation of the general modeling framework. The biological model is based on Sanchirico and Wilen (1999 and 2001) and is in line with the works of Levin (1974, 1976), Hastings (1982, 1983), Vance (1984) and Holt (1985). For a more in depth discussion of this model and general aspects concerning metapopulation modeling, see the above references.

The following equation describes the instantaneous net change in density[1] of sub-population *i*.

(1) $$\dot{x}_i = f(x_i)x_i + d_{ii}x_i + \sum_{\substack{j=1 \\ i \neq i}}^{n} d_{ij}x_j$$

The dynamics of n sub-populations may be expressed in matrix form:

(2) $$\dot{\mathbf{x}} = \mathbf{F(x)x} + \mathbf{Dx}$$

Where

$\dot{\mathbf{x}}$ = n × 1 vector of the instantaneous change in density ($\dot{x}_i$) in patch *i* at time *t*

F(x) = n × n diagonal matrix where the average growth of patch *i* ($f(x_i)$) constitute the diagonal elements

x = n × 1 vector of the level of biomass in patch *i* at time *t* expressed as relative densities. The sum of this vector is the size of the metapopulation.

$\mathbf{D}$ = n × n matrix of dispersal rates (d_{ij})

The growth process of the sub-stocks will be expressed by the logistic growth function. The restriction $\sum_{\substack{i=1 \\ k\neq i}}^{n} d_{ik} = 0$ is imposed on the dispersal matrix and implies that no death or birth occurs during migration, or in other words, the same amount that leaves one patch shows up in another. It is further assumed that $d_{ii} \leq 0$ is emigration from patch i and $d_{ij} \geq 0$ is immigration to patch i from patch j. With this type of model it is possible to describe the most commonly observed links and dispersal mechanisms between the sub-populations (Sanchirico & Wilen 1999): fully integrated systems, closed patches, sink-source and spatially linear systems. Fully integrated systems are systems in which all sub-populations are linked through some dispersal process, while closed systems are comprised of sub-population between which no migration occur. Sink-source systems consist of local populations that are linked through a unidirectional flow of individuals. The last category mentioned, a linearly linked system, is one in which migration only occurs between neighboring patches. This case nests other spatial configurations of patches, such as a circle and a square. The migration may be unidirectional or density dependent. The simplest example of density dependent migration is a two patch system in which $d_{12} = d_{21}$, that is, migration rates from both patches are equal. In this case net migration will always go from the patch with the highest density towards the patch with the lowest density.

The economics

The quota case

In the quota case the harvest function is defined as the standard $H_i = q_i E_i x_i$, where E_i is the fishing effort in patch i, x_i the stock level in patch i and q_i is a constant of proportionality between an increase in effort or stock level and an increase in harvest. We shall assume that $q_i = 1$ in all cases. If one further assumes a patch specific constant cost of effort c_i, and a linear cost function equal to $TC_i(E_i) = c_i E_i$, the cost per unit harvest becomes c_i/x_i. With no growth or death occurring during migration, the migration terms will cancel out when adding the growth of all the stocks. Hence the per period equilibrium rent from the fishery when managed by quotas alone may be expressed by the following function:

$$\pi_Q = \sum_{i=1}^{n} (p - \frac{c_i}{x_i})(r_i x_i (1 - x_i)) \qquad i = 1, 2, \ldots, n \qquad (3)$$

Where p is a constant price and the term in the last parenthesis is the equilibrium harvest and n is the number of patches in the system.

The reserve case

In the reserve case we look at two scenarios regarding the harvest function. In the first case we use the standard Schaefer catch function as in the quota case described above. The variables used in this case will be identified by superscript S. Unlike the quota case, the migration terms does not cancel out in the reserve case and the rent function alters to

$$\pi_R^S = \sum_{i=1}^{m} (p - \frac{c_i}{x_i})(r_i x_i (1 - x_i) + d_{ii} x_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} d_{ij} x_j) \quad i = 1,2, ..,m,\ldots, n \tag{4}$$

Where m is the number of patches in the system in which fishing is allowed, n the total number of patches in the system.

In the case where the harvest function is intended to mimic situations when the fishermen are fishing the line it is assumed that the harvest in patch i at time t depends both on the stock level and the net migration from the reserve at that given point in time. Superscript L identifies variables of this case. Thus, harvest in patch i is defined as $H_i^L = q_i E_i(x_i + d_{ii} x_i + \sum_{\substack{j=1 \\ i \neq j}}^{n} d_{ij} x_i)$. With a the cost function $TC_i(E_i) = c_i E_i$, the cost per unit of harvest now becomes $c_i/(x_i + d_{ii} + \sum_{\substack{j=1 \\ i \neq j}}^{n} d_{ij} x_i)$. Where subscript i denote stock level in the fishable area and subscript j the stock level in the reserve and the two last terms in the parenthesis express the net immigration to the fishable area. The per period equilibrium rent expressed as a function of stock level then becomes

$$\pi_R^L = \sum_{i=1}^{m} (p - \frac{c_i}{x_i + d_{ii} x_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} d_{ij} x_j})(r_i x_i (1 - x_i) + d_{ii} x_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} d_{ij} x_j) \tag{5}$$

$i = 1,2, ..,m,\ldots, n$

Irrespective of assumptions regarding the harvest function, reserve creation is profitable if $\Delta\pi = \pi^*_R - \pi^*_Q > 0$, where the stars are used to indicate that it is the maximum rent possible under reserve and quota regimes. Two main factors determine the sign and size of $\Delta\pi$. First we have what will be called the *dispersal effect*, namely the new equilibrium level of immigration from the reserve to the fishable area due to a larger source stock minus the pre-reserve catch from the closed area. If the net migration from the reserve to the fishable area is greater than the loss of pre-reserve catch, the dispersal effect is positive. The second part is here called the *cost effect* of reserve creation and is caused by the trade off between a higher harvest (the highest harvest is obtained when stock density is 0.5) and a lower cost per unit harvest (the higher the stock density the lower the cost per unit harvest). In the reserve case, with a net flow of fish from the reserve to the fishable area, some of the harvest is "for free", implying that it is unnecessary to reduce stock density to the same extent as in the quota case in order to achieve a given level of harvest. As a result, the cost effect will always pull towards a higher optimal stock level in the fishable area of the reserve case than optimal stock levels of the quota case. The terms will be discussed more thoroughly below. In the following two cases regarding the dispersal process will be examined: A two-patch source-sink system and a two-patch system with density dependent migration.

THE TWO PATCH CASE

Managing the fishery with quotas

For simplicity we shall first assume that the biological and the economic characteristics of the patches are identical. That is, they have the same intrinsic growth rate, carrying capacity, prices and costs. With the biological and economic parameters of the different patches being equal and the restriction that requires the dispersal vector to sum up to zero, the problem of maximizing equilibrium profits from a fishery consisting of two patches becomes

$$(6) \qquad \underset{x_1,x_2}{Max}\ \pi_Q = p\sum_{i=1}^{2} rx_i(1-x_i) - \sum_{i=1}^{2}\frac{c}{x_i}rx_i(1-x_i) \qquad i = 1,\ 2$$

Which is a standard, well-known problem in bioeconomics. Differentiating the profit function with respect to x_1 and x_2, equating these differentials to zero and solving for the x's gives the optimal stock levels

$$(7) \qquad x_{1,\,MEY} = x_{2,\,MEY} = 0.5(1 + c/p)$$

As the cost parameter approaches zero, the optimal stock level (X_{MEY}) in both patches will approach that giving maximum sustainable yield ($X_{MSY} = 0.5$). The greater the cost parameter is compared to the price, the greater the difference between X_{MEY} and

X_{MSY}. If one allows for different harvesting costs in the two patches, optimal stock levels will differ, depending on the patch specific *c/p* ratio. Differences in the intrinsic growth rate will only affect the level of rent, not the optimal stock level.

Managing the fishery with quotas and a marine reserve

Sink-source dynamics

Also here it is first assumed that patches are homogeneous. The two-patch sink-source system may then be described by the following system of equations:

(8)

$$\dot{x}_1 = rx_1(1-x_1) - d_{11}x_1 \qquad \text{Source}$$

$$\dot{x}_2 = rx_2(1-x_2) + d_{21}x_1 \qquad \text{Sink}$$

Where substock 1 would be the source and substock 2 the sink. The parameter d_{11} denotes the migration rate from the source to the sink. But as $d_{11} = d_{21}$ let for notational simplicity $d = d_{11} = d_{21}$ in the following. Since the profitability of marine reserves depends on spillover or migration from the reserve to the fishable area, closing the sink in a sink-source system never pays (Sanchirico & Wilen 2001). Assume therefore that we close the source. The equilibrium stock level in the reserve is found by equating $\dot{x}_1$ to zero and solving for x_1. This gives

(9)

$$\tilde{x}_1 = 1 - d / r$$

With harvesting the equilibrium stock level of patch 2 is determined by solving the following maximizing problem:

(10) $$\underset{x_2}{Max}\ \pi_R^S = (p - \frac{c}{(x_2)})(rx_2(1-x_2) + d\tilde{x}_1)$$

for the case where the Schaerfer catch function is used, and

(11) $$\underset{x_2}{Max}\ \pi_R^L = (p - \frac{c}{(x_2 + d\tilde{x}_1)})(rx_2(1-x_2) + d\tilde{x}_1)$$

for the case where the fishing fleet is assumed to be fishing the line. The analytical solution to theses problems are hard to interpret and it is difficult to isolate the effects of a change in any of the parameters. Hence the discussion below is based on numerical estimates[3]. The equilibrium properties in terms of stability are listed in the appendix. Table 1 gives the parameter values used in the numeric calculations.

Table 1

The numerical estimates show that the optimal stock level in the fishable area depends the *c/p* and *d/r* ratios. As in the quota case, when the costs of harvesting are very low compared to the price, optimal stock level is close to X_{MSY} and increasing with increasing costs, other things equal. This is illustrated in figure 1 where the profit from the fishery when managed with quotas alone is compared to that obtained when managed with both quotas and a marine reserve. The intrinsic growth rate *r* is set equal to 0.4. The cost parameter is adjusted to exhibit three situations. Panel A shows the situation that will be referred to as the low cost case. Here the per unit profit in the quota case is 84.4 % of the price. Panel B illustrates the medium cost case where the per unit profit in the quota case is 50 % of the price. Panel C exhibit a situation were the fishery managed with quotas alone is no longer profitable while the per unit profit as % of the price when managed with quotas and a reserve is 13.6.

The solid black line refers to the quota case, the black line with markers to the reserve case where a Schafer harvest function is used and d = 0.2, r = 0.4. The stippled line reserve(line 1) refers to the case when d = 0.2, r = 0.4. and fishermen are assumed to be fishing the line. The gray solid line reserve(line 2) refers to the case when d = 0.1, r = 0.4. The line reserve(Schaefer) refers to the case where a standard Schaefer catch function is used and the biological parameter values are the same as for reserve(line 1). Subscript is used to identify stock levels under different management regimes, where Q denotes the case of quotas and R the case of quotas and a reserve, superscript to identify sub-populations.

Figure 1

In the sink source case the dispersal effect will be constant for a given cost level, as the flow of individuals is unidirectional. At zero costs the loss of pre-reserve catch is exactly offset by the dispersal from the reserve at optimum. As c increases the dispersal effect becomes positive, or said in an other way, a lower d is required to make the dispersal effect equal to zero. Hence, for a given d an increase in costs causes the dispersal effect to increase. This because while migration from the reserve remains constant, the loss due to reserve creation in terms of pre reserve harvest decreases[4]. The cost effect is reflected in the as costs increase, the optimal stock level of the reserve case increase with more than that of the quota case.

$\Delta\pi$ will always have its' maximum value when $d = r/2$, as this gives the maximum migration from the reserve to the fishable area (see(9)). If $d > r/2$, the stock level in the reserve becomes lower and so do the migration measured in absolute numbers.

We also see from figure 1 that the difference between the results of using a Schafer harvest function and a catch function that mimics a fleet fishing the line is small for a low unit cost of effort, but increasing with increasing cost. In the following the discussion of the sign and magnitude of $\Delta\pi$ will be base on the case where the fishing fleet is assumed to be fishing the line.

For any combination of r and level of harvesting cost, there is one low ($d_l < 0.5r$) and one high value ($d_h > 0.5r$) of d, that gives $\Delta\pi = 0$. The value of d_l decreases with increasing harvesting costs and increases with increasing r. The value of d_h increases with increasing c and r. This is illustrated in figure 2. For all $d_l < d < d_h$, $\Delta\pi > 0$, corresponding to the areas between the gray lines with squared markers in the high cost case, and the black lines with circular markers in the low cost case in figure 2. For $d < d_l$ or $d > d_h$, $\Delta\pi < 0$. We see that the range of migration rates leading to $\Delta\pi > 0$ increases with increasing r and c, everything else constant. Hence, for a specie with a low intrinsic growth rate and/or low harvesting costs (relative to price) marine reserves will have small chances of being profitable, whereas for species with high intrinsic growth rates and/or high harvesting costs, the chances that reserve creation may pay are much greater.

Figure 2

It is also the case that the absolute value of $\Delta\pi$ increases with increasing c and r. This is illustrated in figure 3 where $\Delta\pi$ is plotted for the three cost levels and $d = r/2$.

Figure 3

Allowing for heterogeneity between patches does not alter the qualitative nature of the results only the absolute level of rent generated from the fishery.

Density dependent migration

We first assume that patches are homogeneous in terms of intrinsic growth rates and harvesting costs. The population dynamics of the two-patch system with density dependent migration is described with the following equations:

$$\begin{aligned} \dot{x}_1 &= rx_1(1-x_1) - d_{11}x_1 + d_{12}x_2 \\ \dot{x}_2 &= rx_2(1-x_2) + d_{21}x_1 - d_{22}x_2 \end{aligned} \tag{12}$$

As in the sink source case, $d_{11} = d_{21}$ and $d_{12} = d_{22}$. For notational simplicity let therefore $d = d_{11} = d_{21}$ (the migration rate from patch 1 to patch 2) and $a = d_{12} = d_{22}$

(the migration rate from patch 2 to patch 1) in the following. Closing area 1 gives equilibrium stock size $(\tilde{x}_1)$ equal to

(13) $$\tilde{x}_1 = -\frac{d - r - \sqrt{(r-d)^2 + 4arx_2}}{2r}$$

The maximizing problems in this case are

(14) $$\max_{x_2} \ \pi_R^S = (p - \frac{c}{(x_2)})(rx_2(1-x_2) + d\tilde{x}_1 - ax_2)$$

(15) $$\max_{x_2} \ \pi_R^L = (p - \frac{c}{(x_2 + d\tilde{x}_1 - ax_2)})(rx_2(1-x_2) + d\tilde{x}_1 - ax_2)$$

Optimal stock levels were derived by differentiating (14) and (15) with respect to x_2, equating the differentials to zero, and using the answer to calculate $\tilde{x}_1$ and x_2 numerically. Table 2 gives the parameter values used in the numeric calculations.

Table 2

In figure 4 the equilibrium rent for the different stock densities for both management strategies are shown for the three different cost levels. The stippled curve, reserve(line 1), refers to the case when $a = d = 0.2$ and $r = 0.4$. The gray curve, reserve(line 2) refers to the case when $a = 0.2$, $d = 0.4$ and $r = 0.4$. In panel A the reserve case where a Schaefer harvest function was used is excluded because it coincides with the reserve(line 2).

Optimal stock levels and rent now depends on the parameters *a* and *d* relative to *r*, and the *c*/*p* ratio. Panel A shows the low cost case, panel B the medium cost case and panel C the high cost case. First of all we should observe that reserve creation is unprofitable when the dispersal rates *a* and *d* are equal, unless costs are very high (the situation is not pictured in the figure, but just as in the sink source case, there are situations in which the reserve case is still profitable, but the quota case is not). Secondly, if $d > a$ it may be profitable to create a reserve. Further we see from panel A that for low levels of costs and a low value of the parameter *d* (compared to *a*) the optimal stock level in the reserve is lower than x_{MSY}. This is a result of the dispersal effect, which is no longer constant. When *d* is low, the stock in the reserve is large. Hence it pays to keep the stock level in the fishable area low to ensure a high net migration in absolute numbers. As the value of *d* increases, the stock level within the reserve decreases and the gain in harvest in terms of net migration from the reserve is offset by an increase in the stock level in the fishable area with the following increase in catch and the cost effect. In the low cost case (panel A) we have that when d = 0.38 and $a = 0.2$ the loss of pre-reserve catch is exactly offset by the net migration from the reserve. The corresponding values of *d* in the medium and high cost case are 0.34 and 0.26 respectively.

We also see that the difference in using a Schaefer harvest function and the alternative catch function in the reserve case increase with increasing costs as in the sink-source case.

Figure 4

The trend regarding the change in $\Delta\pi$ following an increase in r and c were also found to be similar to that of the sink source case (see figure 3). Given the value of a, as r or c increases, the relative profitability of reserve creation increases. Also similar to the sink-source case, for a given value of a there is an upper and lower limit to d that makes $\Delta\pi = 0$ and the range between d_l and d_h where $\Delta\pi > 0$ increases with increasing r and c (see figure 2).

If we allow for different harvesting costs in the two patches and density dependent migration the question becomes; which patch should be closed to fishing? Numerical estimates show that it is optimal to close the patch that has the lowest per unit profit as % of the price. This is the opposite result of what Sanchirico & Wilen (2000) found for marine reserves and open access. They found that closing the patch with the highest cost / price ratio would be optimal in the sense of increased harvest. This because with a high cost / price ratio and open access the stock level and hence also equilibrium harvest is low and the loss of pre-reserve catch is less than that for patches with a lower cost / price ratio. In the case of optimal quotas, closing the patch with the highest harvesting costs and thereby the lowest per unit profit, would give the lowest loss of pre-reserve catch. An other interesting result is that with different cost levels and a common migration rate between the patches ($a = d$) reserve creation may be profitable. We have e.g. that if the cost levels are low and medium, or high and medium in the two patches, $\Delta\pi > 0$ when the patch with the highest level of harvesting costs is closed. This result contradicts the conclusions of Sumaila (1998b) and Conrad (1999) that stated that reserve creation was unprofitable in a deterministic setting and density dependent migration with a common migration rate, but in these works differences between the cost levels of the two patches was not taken into consideration.

SUMMARY AND CONCLUDING REMARKS

In this paper the potential for an increase in rent due to reserve creation in a fishery already managed by optimally set quotas has been assessed. This has been done by comparing the per period rent the fishery yields in equilibrium under the two management strategies, assuming two different dispersal mechanisms between the patches; unidirectional and density dependent. Further, two different catch function where used under the reserve case, a standard Schaefer harvest function and a new catch function meant to mimic the behavior of a fishing fleet fishing the line. Through numeric calculations it has been shown that under certain biological and economic circumstances the use of quotas and a marine reserve may be the rent maximizing management strategy.

In the sink-source case it has been shown that the profitability of reserve creation depends on the migration rate relative to the intrinsic growth rate and the cost / price ratio. Furthermore, the higher the costs and the higher the intrinsic growth rate the wider the range of migration rates that allows for profitable implementations of reserves. The profitability of a reserve was also seen to increase with increasing unit cost of effort and intrinsic growth rate. In the case where the patches were assumed to be linked through density dependent migration the profitability of a reserve depends on the rate of migration back to the reserve, the migration from the reserve relative to the intrinsic growth rate in the reserve and the level of costs. It was also shown that reserves where more profitable if the actors where assumed to be fishing the line than when a Schaefer harvest function was used, particularly if unit cost of effort is high.

The results in this paper depend on both on the assumptions made on the biological conditions and the the way the harvesting cost function is formulated. This highlights the need for empirical research; what are the true functional form and parameter values of the harvesting costs function after a reserve has been implemented? An attempt has been made here to mimic what seems to be a common behavior among fishermen participating in fisheries where reserves are part of the management scheme, but the functional form has yet to be tested. Also on the biological side there are some major questions that need to be addressed: What are realistic ranges of values of migration and the intrinsic growth rate? And do the values of the parameters found to make reserve creation profitable fall within the realistic intervals? In addition, there are several complicating factors concerning reserve creation that are not included in this analysis. First we have multispecies dynamics. Assume closing a patch containing both a prey and its predator completely to fishing in order to protect the prey specie. Would there be any gain in terms of spillover of prey, or would it be eaten by an increased predator stock? As an example, Boncoeur et al. (2002) showed that in the case of a reserve containing both a pray, targeted by the fleet, and a predator that is not harvested, the benefits from a reserve in terms of fisheries enhancement are less that the case where multispecies interactions where ignored. Second, the value of catch in an area prior to reserve creation, versus the value of spillover from a reserve is issue that has not been discussed in this paper. Here it has been assumed that these values are equal, although this may not always be the case. E.g. if the migratory part of the stock consist of juveniles or parts of the stock that are in some other way differ from the targeted group prior to reserve creation, the value of the spillover versus pre-reserve catch may be less than what has been pictured here. Hence, many more studies are required before the question of whether reserves enhance fisheries or not are settled.

NOTES

[1] $x = X/K$, where X is the absolute stock level and K is the carrying capacity. In order to calculate absolute growth/harvest from the stock size when it is expressed as relative density, one must multiply the parameter r with K.

[2] $f(x_i) = r_i(1-x_i)$ in (1).

[3] The numerical estimates were conducted in Excel and the file is available from the author at sivr@nfh.uit.no

[4] This is because the optimal stock level is greater than x_{MSY}. Using the logistic growth function to describe population dynamics this implies that an increase in stock level results in a decrease in equilibrium catch.

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APPENDIX. EQUILIBRIUM CHARACTERISTICS.

The Jacobian matrix of the sink-source case is

$$A_{SS} = \begin{bmatrix} r - 2rx_1 - d & 0 \\ d & r - 2rx_2 \end{bmatrix}$$

In the density dependent case:

$$A_{dd} = \begin{bmatrix} r - 2rx_1 - d & a \\ d & r - 2rx_2 - a \end{bmatrix}$$

For all of the parameter values used in this paper we have that the trace of A (tr(A)) is less than zero, the determinant of A ($|A|$) is greater than zero, $tr(A)^2 - 4|A| > 0$ and the eigenvalues are negative when evaluated in optimum, which are the characteristics of an asymptotically stable improper node.

Table 1. Parameter values used quota versus quota s with reserve in a sink-source system.

Parameter	**Value**
p	10
c	1000 in low cost case 3520 in medium cost case 7200 in high cost case
q	1
K_1 and K_2	1000
r	0.4
d_{11} and d_{21}	0.2 for reserve(line 1) and reserve(schaefer) 0.1 for reserve(line 2) (all in figure 1)
d_{12} and d_{22}	0

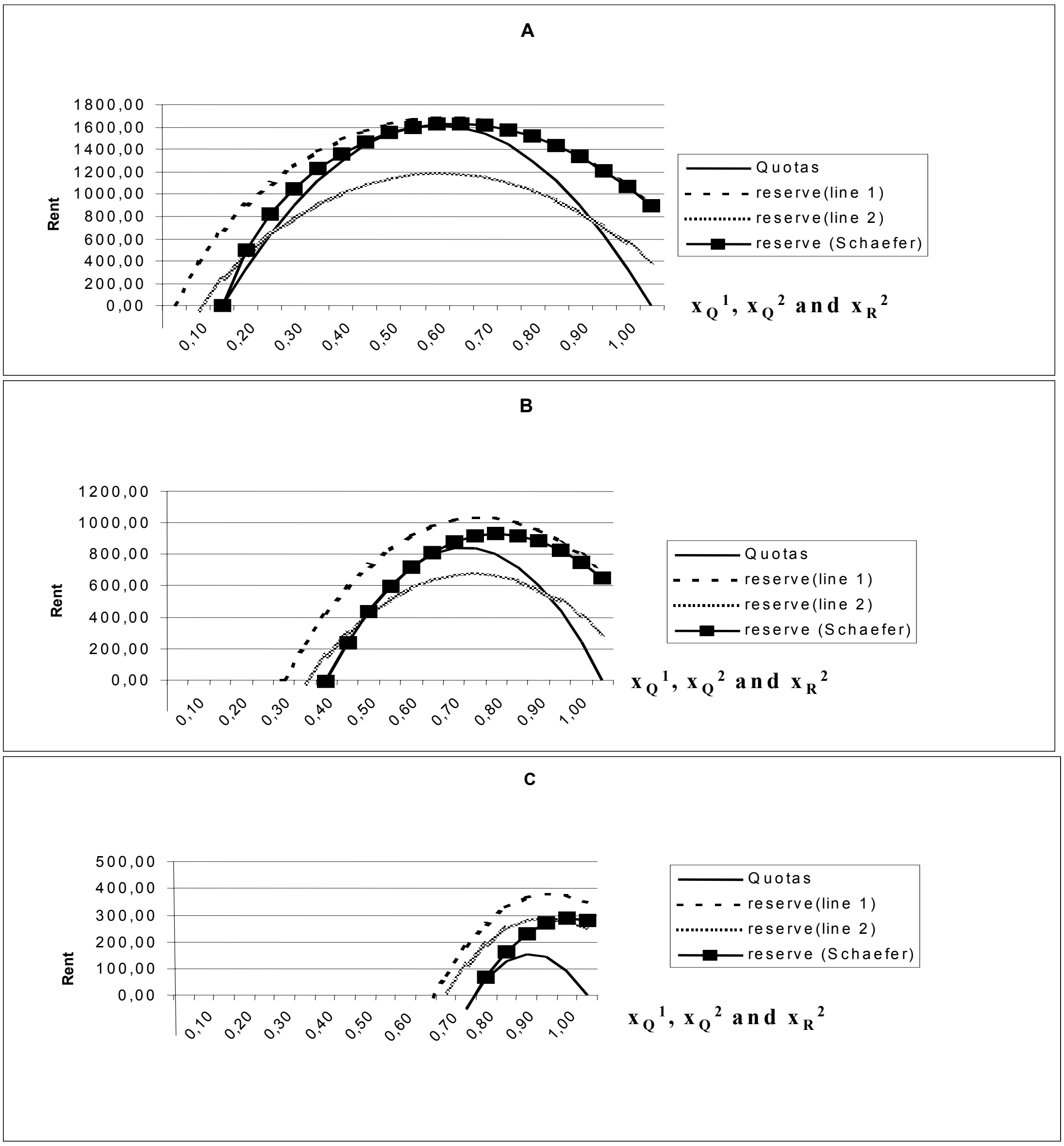

Figure 1. Rent generated from the fishery when managed through quotas alone and with quotas in combination with a reserve when unit cost of effort is low (panel A), medium (panel B) and high (panel C) and with different assumptions regarding migration rates and harvest functions (see text for specifications).

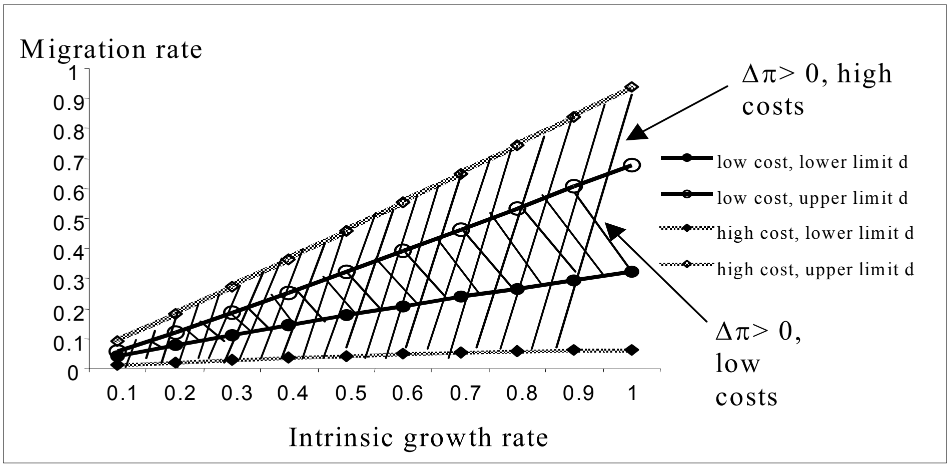

Figure 2. Combinations of the intrinsic growth rate and migration rate that generates $\Delta\pi > 0$ under the assumption that the fleet is fishing the line.

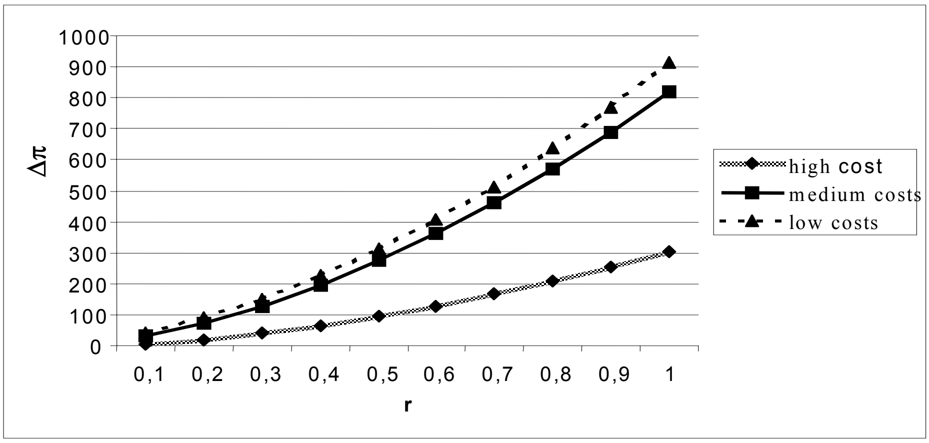

Figure 3. Maximum difference in rent generated from a fishery when managed by quotas alone and when managed by quotas and a reserve as a function of the intrinsic growth rate and for given levels of costs, with migration rate equal to half the intrinsic growth rate.

Table 2. Parameter values used quota versus quota s with reserve in a sink-source system.

Parameter	Value
p	10
c	870 in low cost case 3520 in medium cost case 6400 in high cost case
q	1
K_1 and K_2	1000
r	0.4
d_{11} and d_{21}	0.2 for reserve(line 1) and reserve(schaefer) 0.4 for reserve(line 2) (all in figure 4)
d_{12} and d_{22}	0.2

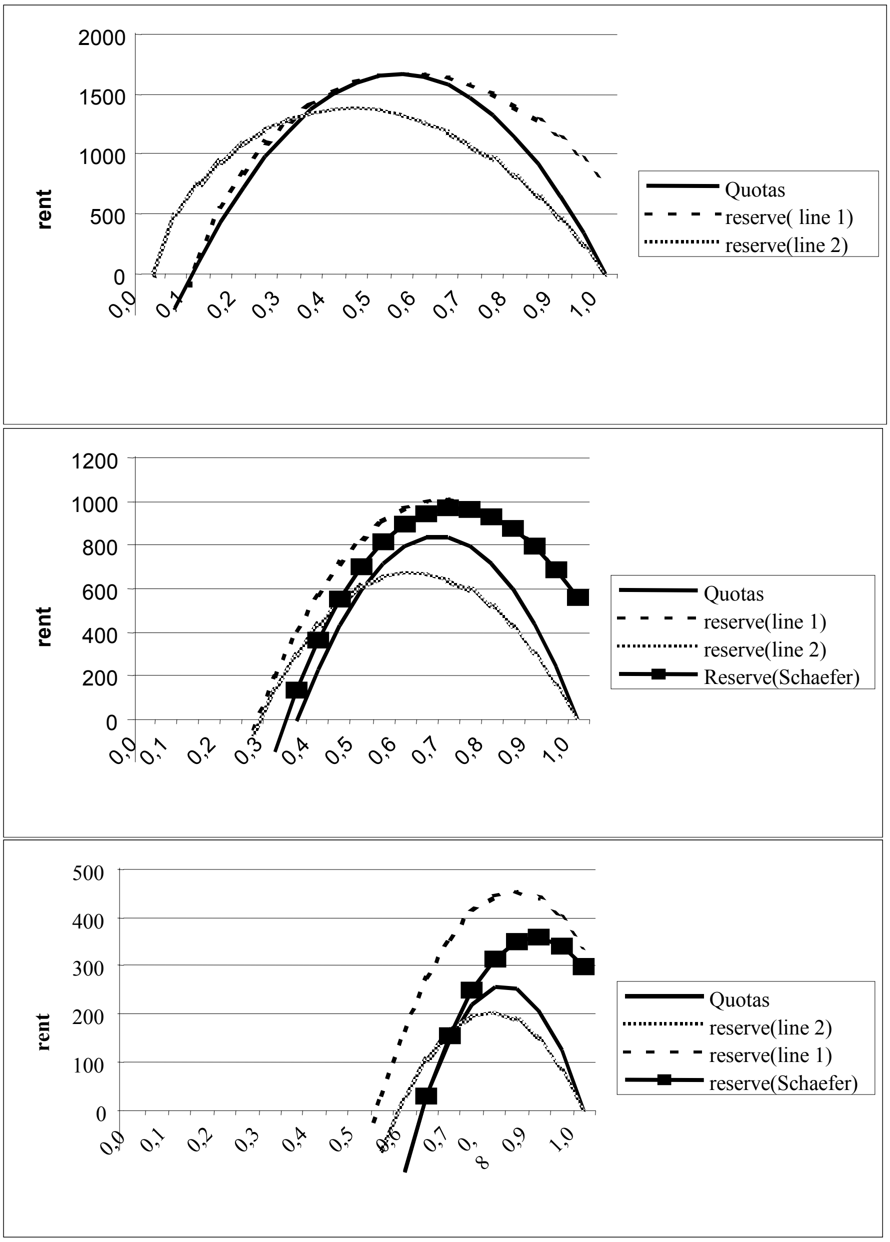

Figure 4. Rent generated from the fishery in the medium cost case when managed by quotas alone and with quotas in combination with a marine reserve.