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Protected marine reserves as fisheries management tools: a bioeconomic analysis

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Abstract

This paper develops a dynamic computational bioeconomic model with the objective of assessing protected marine reserves as fisheries management tools. Data on the North East Atlantic cod stock are used to determine the bioeconomically optimal size of a marine reserve for the Barents Sea cod fishery, as a function of the net transfer rate between the protected and unprotected areas of the marine habitat. The single agent model developed, allows for the occurrence of a shock to the system in the form of severe recruitment failure in the non-protected area. Two key results emerge from the study. First, establishment of marine reserves are bioeconomically beneficial when net transfer rates for cod are 'reasonably' high and reserve sizes are large: large reserves provide good protection for the stock in the face of the shock, while high transfer rates make the protected fish available for harvesting after the shock has occurred. Further, optimally chosen reserve size when net transfer rates are high, also mitigates against biological losses. Second, when net transfer rates are low, the establishment of marine reserves does not mitigate against losses in the discounted economic rent, while they tend to be efficient in mitigating against biological losses.

Keywords: Uncertainty; Net transfer rates; No-fishing areas; Biological; Economic; Trade-offs

1. Introduction

The purpose of this paper is to address the gains and losses in economic rent, catches, and standing biomass that may result from the establishment of protected marine reserves (PMRs), defined as no-fishing zones. Increasingly no-fishing zones are seen as useful fisheries management tools in the face of disappointments with present management practices. Generally, the establishment of PMRs has been promoted as a viable alternative when other forms of fisheries management are impracticable or unsuccessful (see for instance, Wallis, 1971; Davis, 1981; Bohnsack, 1990). Bohnsack (1990) gives a comprehensive list of the potential benefits that may be expected from the establishment of marine reserves, including (i) protection of spawning biomass, (ii) providing a recruitment source for the surrounding areas, (iii) supplemental restocking of fished areas through emigration, (iv) maintenance of natural population age structure, (v) maintenance of areas of undisturbed habitat, and (vi) insurance against management failures in fished areas.

To realize any, or all, of the potential benefits listed above, biologists argue that PMRs must be designed

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appropriately: *location*, *size* and *shape* of the reserve must be chosen to reflect the realities of the habitat and the fishes to be protected (see for example Rowley, 1994). A number of scientists have looked at the question of the optimal size of protected marine reserves from both the biological and the mitigation of the effects of uncertainty perspectives. Polacheck (1990), Quinn et al. (1993) and Man et al. (1995), all come to the conclusion that for the effects of protection to be realized, a reserve must be about 50% of the habitat. Lauck et al. (in press) suggest that the negative impacts of uncertainty may be mitigated if large parts of the fish population (at least 50%) is protected completely from exploitation. The current paper extends past studies by exploring optimal bioeconomic marine reserve size in the face of a shock to the system. This effort is a follow up to Sumaila (in press), where the case for the inclusion of social and economic variables in the assessment of marine reserve as a fisheries management tool is made.

The rest of the paper is organized as follows. In the next section, I present the model, which consists of two parts: a main model that describes the dynamics in the fished area, and a subsidiary one which does the same for the protected area. The two parts are linked through a net transfer rate function. In Section 3, the results of the study are stated, the main highlight of which is that optimal PMR size is zero in a single agent bioeconomic model when the net transfer rate is low. However, when net transfer rates are high, the optimal size is positive. Section 4 discusses the results of the study and concludes the paper.

2. The model

The analysis focuses on the Barents Sea cod fishery in quasi-empirical manner, but it could be replicated for any fishery for which the necessary data are available. The Barents Sea cod stock is controlled by Norway and Russia, both of which have legitimate claims to fishing rights to the stock. Let us assume that both the countries have the objective of managing the resource in a bioeconomically efficient manner. They recognize the need to cooperate so as to eliminate all common property problems, and so get rid of both biological and economic waste of the resource. This implies that given full and perfect information about the fishery, these countries would deploy the exact amount of fishing effort every year to ensure them maximum discounted economic rent from the resource, without destroying the resource base. Indeed, management of the Barents Sea cod has been characterized by cooperation between Norway and Russia over the years: Total allowable catches are determined annually based on work carried out by scientists from the two countries, and allocation decisions made by a mixed Norwegian-Russian Commission (Nakken et al., 1996).

Being realistic rational agents, the countries recognize that to have full and perfect information about the fishery is but a dream because of true uncertainty (see Lauck et al., in press; Sumaila, in press). In furtherance of the ongoing cooperation between the two countries, and as a way to mitigate the negative impacts of the inadequacy of information available, the countries consider the establishment of protected marine reserves. The key question then is, what is the bioeconomically optimal size of the proposed PMR? This is the main question addressed in this paper.

2.1. Recruitment of cod to the habitat

Let recruitment of age 0 fish to the whole habitat in period t (t=1, $\cdots$, T), R_t, be represented by the following Beverton-Holt recruitment function. This function is chosen because recent biological studies have shown that it is more realistic than the Ricker recruitment function (Guenette and Pitcher, pers. Comm.),

$$R_t(B_{t-1}) = \frac{\alpha B_{t-1}}{1+\gamma B_{t-1}} \tag{1}$$

where $B_{t-1} = \sum_a p_a w_{s,a} n_{a,t-1}$ represents the post-catch spawning biomass of fish in weight; p_a is the proportion of mature fish of age a(a=1, $\cdots$, A); $w_{s,a}$ is the weight at spawning of fish of age a; $n_{a,t\text{-}1}$ is the post-catch number of age a fish in period t−1; and α and γ are constant biological parameters. The values of α and γ determine the amount of recruitment into the habitat for a given spawning biomass, which in turn determines the pristine stock level in a deterministic model.

2.1.1. Modeling protected areas

To establish reserves in the model, the following assumptions are made, (i) initially, the stock and recruits are homogeneously distributed, and randomly dispersed at a constant density, (ii) the fish population in the habitat can be split into two distinct components, i=1,2 where 1 and 2 denote the protected and unprotected areas, respectively, and (iii) there is net movement from the protected to the unprotected area, because presumably fish density is high relative to the carrying capacity in the protected compartment (see the Basin model, MacCall, 1990). This movement is captured by a biological function known as the *net transfer rate*, which tells us the net proportion of a given age group of fish that is transferred from the protected to the unprotected area in a given fishing period. Note that the net transfer rate is a biological characteristic of the stock studied. There are a number of biological studies that have attempted to model the transfer rate for particular fisheries (see for example, Polacheck, 1990). In this study attempts are not made to determine a particular net transfer rate for cod, rather results for a set of transfer rates are produced, and the reserve size that gives the best bioeconomic outcome for each of these are determined.

2.2. Dividing habitat into protected and unprotected areas

Three things are done in order to divide the habitat into protected and unprotected areas. First, the initial stock size in the habitat, as a whole, is divided between the protected and unprotected areas in proportion to their respective sizes. Hence, a size of PMR of 30% of the habitat, results in a split of the initial stock size into a 3:7 ratio in favor of the unprotected area. Second, recruitment into the two areas are separated and defined as in Eq. (1) above, each area with its own B^i_{t-1} and γ^i, i=1,2. The α parameter, being an intrinsic element of the stock under consideration, is kept constant both for the fish in the reserve and those in the fished area. Third, the respective γ parameters are set such that (i) the sum of recruitment from both areas satisfy

$$R^1_t + R^2_t = R_t \quad \text{for } B^1_{t-1} + B^2_{t-1} = B_{t-1} \qquad (2)$$

and (ii) the recruitment into the protected and unprotected areas is directly related to the quantity of the total biomass in them. These conditions are enforced by giving γ^i values dependent on the reserve size.

2.3. The stock dynamics

For the protected area, let the stock dynamics of the biomass of fish in numbers, $n^1_{a,t}$, be described by

$$n^1_{0,t} = R^1_t \qquad (3)$$

$$n^1_{a,t} + \psi n^1_{a,t} = s n^1_{a-1,t-1} \quad \text{for } 0 < a < A,$$

$$n^1_{A,t} + \psi n^1_{A,t} = s(n^1_{A-1,t-1} + n^1_{A,t-1}) \quad n^1_{a,0} \text{ given}$$

where the parameter s is the natural survival probability of cod, assumed to be age independent; $\psi n^1_{a,t}$ is the net transfer function through emigration from the protected to the unprotected area of age a cod in period t, and ψ is a fraction; $n^1_{a,0}$ denotes the initial stock level in the protected area, which is a fraction (equal to size of reserve) of the initial stock level in the habitat. It should be noted that there is no direct harvesting of cod in the reserve.

The stock dynamics in the unprotected area may be expressed as

$$n^2_{0,t} = R^2_t \qquad (4)$$

$$n^2_{a,t} + h^2_{a,t} = s n^2_{a-1,t-1} + \psi n^1_{a,t} \quad \text{for } 0 < a < A,$$

$$n^2_{A,t} + h^2_{A,t} = s(n^2_{A-1,t-1} + n^2_{A,t-1}) + \psi n^1_{A,t}, n^2_{a,0} \text{ given.}$$

where $h^2_{a,t} = q_a n^2_{a,t} e_t$ is the harvest function; q_a is the age dependent catchability coefficient, and e_t, the effort employed in the exploitation of cod in period t.

2.4. A shock to the system

The shock introduced herein is due to what is described in the literature as true uncertainty (see Lauck, et al., in press; Walters and Hilborn, 1978). By definition true uncertainty is difficult to model, as it comes in the form of an unexpected disaster, or catastrophe, with a huge negative impact. True uncertainty is introduced here in a simple manner: The occurrence of a shock to the system is added to the otherwise deterministic model. The particular shock incorporated is a recruitment failure (zero recruitment) that occurs in years 5–15 (inclusive) of the 28 year-time horizon model. An important point to note here is that the shock is assumed to occur only in the fished area, an assumption which follows Lauck et al. (in press), where true uncertainty is assumed to occur because of human intervention (based on imperfect information) in the natural environment, which leads to both unintended over-fishing and habitat degradation. The reader may want to compare the use of uncertainty here with its use in other papers in this volume.

A variety of possible shocks could have been introduced in the model, a particular shock introduced would be expected to have at least some quantitative effect on the results of the analysis. In designing the shock in this model, the aim was to get something dramatic enough to capture the concerns of the analysis. After all, true or second degree uncertainty is concerned with dramatic shocks such as the one which led to the suspension of commercial fishing in Atlantic Canada's cod fishery since 1992. Anyhow, sensitivity analysis allowing a less dramatic shock to the system is performed to investigate the consequences of such changes to the results of the study.

2.5. Management objective

In terms of management, the net transfer rate is a biological characteristic of the stock being studied, while PMR size, and size of catch (or equivalently effort level) are choice variables for management. The objective of the cooperative owners is to find a sequence of effort levels, e_t (t=1,2, . . . ,T=28) to maximize the discounted economic rent from the resource for given PMR sizes, as a function of the net transfer rate. That is, maximize

$$\Pi(n^2, e) = \sum_{t=1}^{T} \delta^t \left(v \sum_{a=0}^{A} w_a q_a n^2_{a,t} e_t - \frac{k}{1+b} (e_t)^{1+b} \right) \tag{5}$$

with respect to the effort level given the size of the PMR, and subject to (i) Eq. (3), (ii) Eq. (4), and (iii) the necessary non-negativity constraints. It should be noted that the maximization is carried out under full information in the face of a shock to the system.

In Eq. (5) above, $\delta = (1+r)^{-1}$ is the discount factor, and r denotes the interest rate, n^2 the age and time dependent stock size matrix in the fished area; v is the price per unit weight of cod; w_a the average weight of age a cod; k a cost parameter, and b>0 a parameter introduced to ensure strict concavity, which is required to ensure convergence in the model (see Sumaila, 1997). It should be noted that the cost function in (5) is independent of the size of the reserve. This is a simplification as one would expect harvesting cost to be directly related to the size of the reserve due to factors such as the effects of congestion on harvesting activities. On the other hand, one can also argue that given the current state of fishing technology, it is possible to land fish at unit costs that are space-independent.

The following modified Lagrangian function can be set up for the problem expressed in Eq. (5) (see Sumaila, 1997).

$$\begin{aligned} L(n^1, n^2, e, Tr^{12}, y) &= \Pi(n^2, e) \\ &+ \sum_{t=1}^{r} \begin{bmatrix} y^1_{0,t}[R^1_t - n^1_{0,t}]^- + y^2_{0,t}[R^2_t - n^2_{0,t}]^- \\ +y^1_{A,t}[s(n^1_{A-1,t-1} + n^1_{A-1,t}) - n^1_{A,t} - \psi n^1_{A,t}]^- \\ +y^2_{A,t}[s(n^2_{A-1,t-1} + n^2_{A-1,t}) + \psi n^1_{A,t} - n^2_{A,t} - h^2_{A,t}]^- \\ + \sum_{a=1}^{A-1} y^1_{a,t}[s n^1_{a-1,t-1} - n^1_{a,t} - \psi n^1_{a,t}]^- \\ + \sum_{a=1}^{A-1} [y^2_{a,t} s n^2_{a-1,t-1} + \psi n^1_{a,t} - n^2_{a,t} - h^2_{a,t}]^- \end{bmatrix} \end{aligned} \tag{6}$$

where the variable y is a modified Lagrange multiplier; a 'negative' superscript to a bracket, [.]-, refers to the min(0,[.]) and all other variables and parameters are as defined earlier.

The solution to the problem at hand is pursued numerically using a procedure from non-smooth convex optimization (Flåm, 1993). The computational novelty here lies in the fact that two separate but linked models are simulated: a main model capturing the dynamics in the fished area, and a co-model that captures the dynamics in the protected area. The two models are run in parallel, linked through the net transfer rate function.

3. The results

3.1. Data

The parameters α and γ are set equal to 1.5 and 1 per billion kilograms, respectively, to give a billion zero age fish when the spawning biomass is two million tons. Based on the survival rate of cod, s is given a value of 0.81 for all a. The price, v=NOK 6.78, is assumed to be constant and age independent. The cost parameter k, which denotes the cost of engaging a trawl vessel for one year, is calculated to be NOK 21 million (see Sumaila, in press) The discount factor is given a value of 0.98 to reflect the current low level of interest rates. The initial number of cod of age groups 1 to 8 are obtained by taking the average of the initial numbers from 1984 to 1991 reported in Table 3.12 of the Anon. (1992). For the other age groups we assume the same number as for age group 8. This gives (460,337,298,223,117,61,33,9,9,9,9,9,9,9,9) for a= 1.15, resulting in an estimated initial stock size of 2.24 million tons. The parameter p_a=0 for a<7 and 1 otherwise; q_a=0 for a<5 and 0.074 otherwise; w_a= (0.1,0.3,0.6,1.0,1.4,1.83,2.26,3.27,4.27,5.78,7.96,9.79,11.53,13.84,15.24,16.34) for a=$0..15$; and $w_{s,a}$ is assumed to be 90% of w_a (see Sumaila, 1995).

3.2. Discounted economic rent

First, the results for an *experimental* scenario, where no PMR is in force in the presence of a shock to the system (denoted 'expt'), and a control scenario, where there is no shock and no PMR in force, are presented. For the control scenario, a discounted economic rent of NOK 109.29 billion is computed, while NOK 53.79 billion discounted economic rent is obtained in the case of the experimental scenario. Thus, over 50% of the possible economic benefits from the resource are lost as a result of the shock to the system. These two outcomes are the base case scenarios with which comparison would be made with the outcomes for scenarios in which PMRs are in force.

The discounted economic rent obtained for different reserve sizes (ranging from 0.1 to 0.7), and for different net transfer rates (ranging from 0.1 to 0.6) are reported in Table 1. The maximum net transfer rate of 0.6 is chosen based on the fact that a demersal species such as cod is not expected to have too high net transfer rates. Similarly, the maximum PMR size of 0.7 is selected because size of PMR of over 0.7 of habitat is considered to be unrealistic, especially because dependency of harvesting cost on PMR size is not modelled in this paper. Also the fact that it is implicitly assumed that the number of fish transferred from the reserve to the exploited area increases with the size of the reserve, makes higher reserve sizes unrealistic.

To read Table 1 start from the first column and select a particular net transfer rate, then read across the row for this net transfer rate and identify the highest figure in the row. Now, pick out the reserve size that corresponds to this and that is the PMR size that gives the highest discounted economic rent for the chosen net transfer rate. For instance, for a net transfer rate of 0.3, the highest economic rent achievable is NOK 49.93, corresponding to PMR size equal to 0.1. A point to note from Table 1 is that the rent reported is not unimodal as would be expected. A possible reason for this is the complex nature of how the transfer rate, reserve size, recruitment, etc., interact with each other in the model.

A comparison of the payoff of NOK 53. 79 achieved under the experimental regime, with the highest payoffs for each of the possible net transfer rates in Table 1 shows that economically, optimal PMR size is 0 for net transfer rates ranging from 0.1 to 0.3. This means that for low net transfer rates, the cooperative agents are better off without creating a protected marine reserve. On the other hand, we see that for high net transfer rates (0.4–0.6), the optimal PMR size

Table 1
Presents discounted economic rent (in billion NOK) obtained as a function of both PMR size and the net transfer rate.

	PMR-size						
Trans rate	0.1	0.2	0.3	0.4	0.5	0.6	0.7
0.1	48.25	42.38	39.06	35.3	30.64	26.39	28.23
0.2	49.53	44.58	42.27	40.33	36.66	35.1	38.87
0.3	49.93	47.55	45.37	43.47	40.69	41.33	45.53
0.4	50.25	48.22	47.96	46.36	44.49	50.26	55.52
0.5	51.25	50.14	50.91	49.72	50.49	57.27	65.94
0.6	52.69	51.8	54.91	54.06	58.04	63.67	68.94

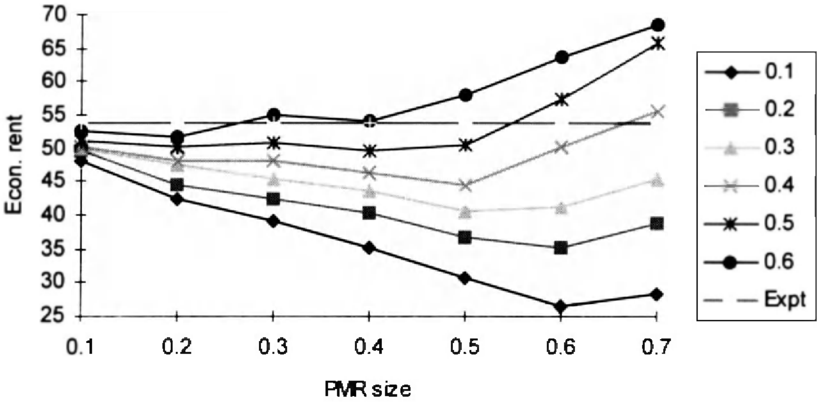

Fig. 1. Plots discounted economic rent (in billion NOK) against PMR size for each possible net transfer rate, and the experimental scenario.

jumps to as high as 0.7. This means that the establishment of marine reserves in this model mitigates against economic loss only if cod is a fast mover. The two results stated above are illustrated more clearly in Fig. 1. In this figure, discounted economic rents are plotted against PMR size for each possible net transfer rate including the experimental case. From the figure we see that a comparison of the plot for the scenario where no PMR is created, shows that the establishment of PMR is economically beneficial only for a combination of high transfer rates (0.4–0.6) and large reserve sizes (0.4–0.7).

3.3. Stock level

Fig. 2 shows that the establishment of a PMR in the face of a shock to the system is clearly biologically beneficial: in all cases and throughout the time horizon of the model, the plotted stock profiles are higher than for the experimental scenario. Also, at the terminal

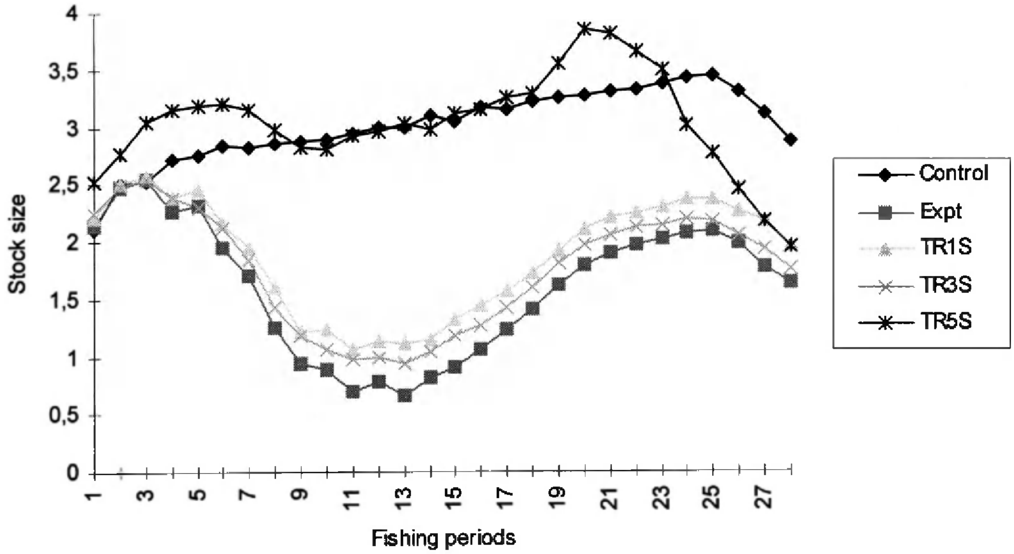

Fig. 2. Plots the stock profiles (in million tons) for the control, experimental (expt), and those that give the highest economic benefits for net transfer rates equal to 0.1 with PMR size =0.1 (TR1S); 0.3 with PMR size =0.1 (TR3S); and 0.5 with PMR size =0.7 (TR5S).

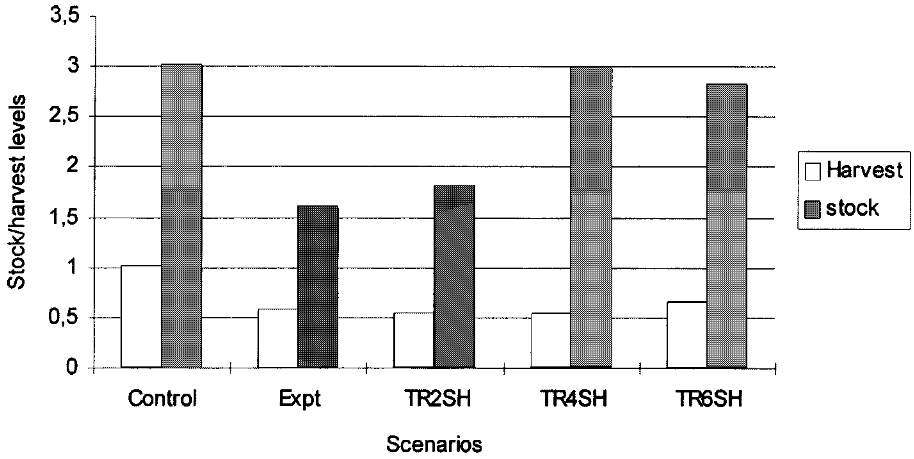

Fig. 3. Plots the average stock and harvest levels (in million tons) for the control, experimental (expt), and those that give the highest economic benefits for net transfer rates equal to 0.2 with PMR size =0.1 (TR2SH); 0.4 with PMR size =0.7 (TR4SH); and 0.6 with PMR size =0.7 (TR6SH).

period, lower stock of fish is left in the experimental case. It is worth mentioning at this juncture that the fishing pressure indicated by the stock and harvest profiles during the last periods of the game is mainly because of the fact that the end of the game is approaching: Hence, the fishers are trying to do their best before the arrival of the 'doomsday'. These results are further illustrated by Fig. 3, which plots the average stock and harvest levels for the different scenarios. A comparison of the average stock levels in the presence and absence of a reserve, shows that their establishment acts as a hedge against biological losses in the face of a shock to the system.

Another point to note from Fig. 3 is that, for the same reserve size, higher net transfer rates for the same (reserve) size results in lower average standing biomass (compare the bars for TR4SH with those for TR6SH, where in each case reserve size is 0.7). On the other hand, higher net transfer rates imply higher harvests, and thus higher economic benefits. Clearly, at some point there is an inevitable trade-off between biological and economic benefits of marine reserves, an issue discussed later in this section of the paper.

3.4. Catch level

Figs. 3 and 4 demonstrate the effects of the establishment of marine reserves on the harvest levels. We can conclude from these figures that high net transfer rates are important for ensuring minimal or no losses in harvest levels with the creation of marine reserves.

3.5. Sensitivity analysis

With respect to sensitivity, the most important assumption of the study is that related to the shock introduced in the model. To test how sensitive the results are to the dramatic recruitment failure in years 5–15 assumed in the base scenario, the model is re-run with a milder recruitment failure, which occurs only in years 4–8 of the 28 year time horizon model. Two observations were made. First, as expected, the need for no-fishing zones both in terms of economics and biology reduces when a less dramatic shock is incorporated. Second, the importance of high net transfer rates, for making the establishment of PMRs economically defensible, is further reinforced with a milder shock.

The effects of changes in economic parameters such as the discount factor and net price per unit weight of fish landed reported in Holland and Brazee (1996) are valid here. That is, an increase in the discount factor will tend to increase the optimal size of marine reserve required. Also, increasing net real price of fish over time will support larger optimal reserve size than for constant or decreasing net prices.

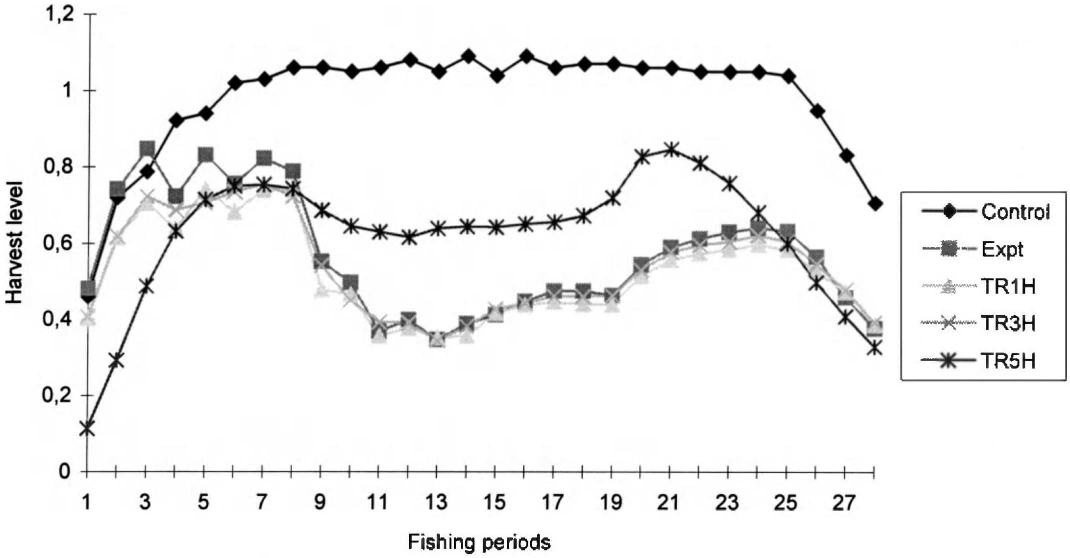

Fig. 4. Plots the harvest profiles (in million tons) for the control, experimental (expt), and those that give the highest economic benefits for net transfer rates equal to 0.1 with PMR size =0.1 (TR1H); 0.3 with PMR size =0.1 (TR3H); and 0.5 with PMR size =0.7 (TR5H).

3.6. Economic and biological gains: an analysis of trade-offs

Apart from determining the optimal size of marine reserves for a given fishery, studies of this nature can help make clear trade-offs between biological and economic concerns related to their establishment. It should be noted that throughout this paper, stock size and discounted economic rent are taken to be the indicators of biological and (bio)economic health of the fishery, respectively. To discuss these trade-offs, let us assume that the net transfer rate for cod has been determined to be 0.2. For this net transfer rate, Fig. 5 plots average standing stock sizes, a biological safety

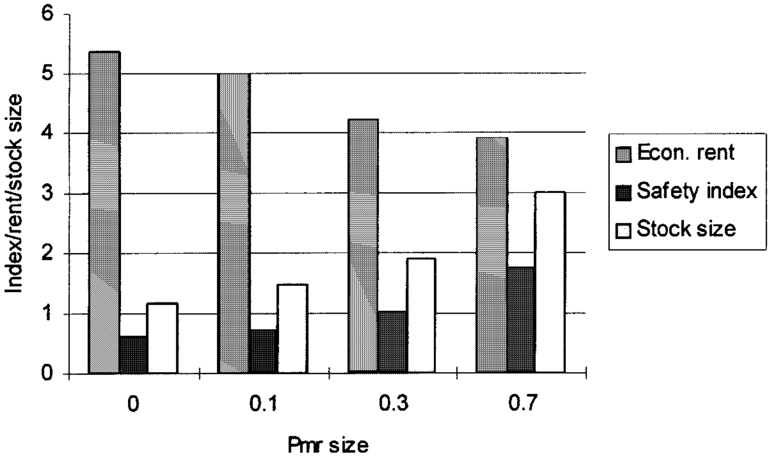

Fig. 5. Plots average standing stock sizes (in billion tons), biological safety index and discounted economic rents (in 10's of billion NOK), against reserve size for net transfer rate of 0.2.

index, and discounted economic rents, against reserve size. Following the way price indices are defined (Gordon, 1986 ch. 2), the index of biological safety is defined as, average standing spawning biomass less minimum safe level of spawning biomass, divided by minimum safe level of spawning biomass. This definition implies that the larger the index the more biologically safe the stock, or conversely, the lower the index the more risk the stock faces.

Russian and Norwegian scientists have come to the conclusion that the minimum safe level of spawning biomass for the North East Atlantic cod is 0.5 million tons (Jakobsen, 1993; Serebryakov, 1991). Using this information and the spawning biomass computed, indices of biological safety for the different scenarios are calculated and used to plot Fig. 5.

From Fig. 5, it is seen that as reserve size increases from 0 to 0.7, economic rent decreases from 53.79 to 38.87 billion NOK. However, the average stock size increases from 1.6 to 3.09 million tons. Furthermore, the figure shows that the larger the reserve size the more biologically safe the stock. Thus, the more safe we want the stock to be (into the future) the less economic benefit we can achieve now.

The question facing management therefore is, how much biological safety is it willing to trade-off for more current economic benefits, and vice versa? The answer to this question would depend on how risk averse the management is: a very risk averse management would go for a reserve size of 0.7, accepting a discounted economic rent of NOK 38.87 billion and maintaining a high safety index of 1.72. An index of 1.72 means that a spawning biomass of 1.72 times the required minimum is maintained. On the other hand, a risk loving management would choose a reserve size of zero (or 0.1), accepting a low safety index of 0.6 (0.7), in order to make a discounted economic rent of NOK 53.79 (49.53) billion.

4. Discussion and conclusion

Results from studies that focus on the problem of uncertainty suggest that large reserves have the potential to mitigate the negative impacts of true uncertainty (Lauck et al., in press). From the bioeconomic perspective, the current study supports this results for a model that incorporates a shock to the system, but only in the case of fast moving fish. In terms of hedging against biological losses, however, this study supports the results of Lauck et al., in press, without reservation.

The results from previous biological studies of marine reserves can be summarized in the following three points (see Guenette et al., in press). The establishment of marine reserves will result in (i) an increase in the spawning biomass, (ii) a decrease in the fishery yield or harvest, and (iii) movement of fish out of the reserve could negate its benefit. It should be noted that these results fit reasonably well with those of the current study, especially if we consider the fact that the studies cited are biological studies of fisheries where over-exploitation is the main concern: In a single agent model of the type developed herein, 'delibrate' over-exploitation is not a problem.

As modeling and computations are exercises in successive approximation, there are a number of aspects of the current study that can to be improved upon. First, the transfer rate function is assumed to be proportional to the size of the protected stock. This is clearly simplistic as the size of a reserve will impact on how much of the fish in the protected area will be transferred to the fished area. In addition, the way it is modelled, the productivity of the stock increases with the size of the reserve, which might not be realistic at low transfer rates, since the reserve compartment might increase to near carrying capacity with no room for further recruitment.

I see the proportionality assumption as an economist's simplification of the biological processes involved and a challenge to biologists to develop more realistic transfer rate functions, as these are crucial to any analyses of the potential benefits of marine reserves. The current study produces preliminary results that, I hope, will stimulate fisheries researchers (biologists, economists and other social scientists) to look deeper into a line of research which will became increasingly more important as we strive to find better ways to exploit the world's fishery resources sustainability.

In addition to the modeling of the transfer rate function, I can foresee at least three possible improvements and extensions to the current analysis. First, an extension of the model to make it multi-agent and non-cooperative should provide interesting insights because then, it would be possible to explore the effects of non-cooperation on the bioeconomic usefulness of protected marine reserves. Second, an improvement in the cost function used in this analysis could be achieved by remodeling it to make it dependent on the size of the reserve. Third, introduction of stochasticity in the model will be a useful extension, as this will make it a true model of uncertainty.

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