Increasing marginal returns and the danger of collapse of commercially valuable fish stocks[†]

Jose M. Maroto[a] and Manuel Moran[b,*]

[a]Department of Estadística e Investigación Operativa II.

[b]Department of Fundamentos del Análisis Económico I.

Both at Universidad Complutense, 28223 (Madrid), Spain.

Corresponding author. PHONE: +34913942407, FAX: +34913942561.

E-mail addresses: maroto@ccee.ucm.es, mmoranca@ccee.ucm.es (M. Moran*)

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Abstract

On the basis of data from the North Sea herring fishery, we discuss the consequences of increasing marginal returns on the exploitation of renewable resources. We show that high, but still reasonable, discount rates can cause extinction to be optimal even in the ideal case of a sole owner and a resource with a high growth rate. In the case of lower discount rates, optimal cyclical policies can periodically drive the resource to levels approaching Safe Minimum Standards. We discuss the sustainability, intergenerational equity, social risk aversion, and theoretical issues raised by increasing marginal returns.

Keywords: Dynamic programming; Precautionary Approach; Bioeconomic modelling; Stock collapse; Lipschitz continuity; Increasing marginal returns.

1 Introduction

There is increasing empirical evidence of the severe worldwide depletion of commercially valuable fish stocks. According to the FAO (2004), 75% of all commercially valuable fish stocks are exploited. Moreover, Myers and Worm (2003) show that all commercially important fisheries in the world are heavily overexploited (see also Sterner and Svedäng, 2005).

Internationally, the significance of stock collapse is well understood and has led to widespread endorsement of the Precautionary Approach, which attempts to manage fish stocks within safe biological limits established by the International Council for the Exploration of the Sea (ICES). The term "collapse" is used to signify that the stock has reached a level where it suffers from severely reduced productivity (ICES, 2005a). Important marine fisheries that have already reached this situation are, among others, Atlantic cod, Pacific sardine, haddock, Bering wolffish, Atlantic halibut (Hutchings, 2000). In these cases, recovery is likely to be slow and will depend on effective conservation measures. Hutchings (2000) stresses that many fisheries which have suffered dramatic population reductions have experienced little, if any, recovery. According to this author, worldwide overfishing has raised concerns that the risk of extraordinary collapse in abundance may significantly increase due to the complex interlinking of ecological systems and the extinction probability of both targeted and incidentally harvested marine fishes. This means that if a stock is in danger of collapse, biological extinction might occur with an unknown and, hence, potentially positive probability due to the effect of additional environmental shocks negatively affecting reproduction capacity.

Environmental damages and overfishing due to fishery overcapitalization combined with inaccurate fishing quotas are the most generally accepted causes of the precarious situation of fish stocks. From a theoretical point of view, this situation is a direct result of the high discount rates applied by fisheries and political institutions. Hillis and Wheelan (1994) show that the large magnitudes of fishermen's discount rates (rates range from 25% to 40%) are mainly due to the great uncertainty perceived about future landings (see also Döring and Egelkraut, 2007). This implies little concern about future stocks, as predicted by the Gordon-Schaefer model in an open access regime (Gordon, 1954; Schaefer, 1957). Accordingly, one of the main lines of research in fisheries literature focuses on suitable alternatives to the property rights issue (Sterner and Svedäng, 2005; Döring and Egelkraut, 2007; Sterner, 2007).

The aim of this paper is to warn about the existence of increasing marginal returns as an additional explanation for the current high risk of collapse observed in fisheries worldwide. The existence of increasing marginal returns not only might invalidate standard solutions based on property rights regulation, but it also has implications in optimal policy dynamics, which in turn affects intergenerational equity, sustainability, and social risk aversion issues. Similar consequences could be relevant to the economic exploitation of other renewable resources where increasing marginal returns operate (Dasgupta and Mäler, 2003).

The most prominent feature of increasing marginal returns in resource management is that, if the resource is managed by a sole owner, the present value optimizing policy tends to be cyclical, and the optimal cycle is quickly attained without a relevant delay, in contrast with the monotone paths converging to a steady state that follow from the standard assumptions of concavity in the return and the growth functions. Thus, standard optimal policies based on the constant escapement rule can be suboptimal due to the effect of increasing marginal returns.

In this paper, we use a standard present value optimization model with data from the North Sea herring fishery. The objective is to show that optimal cyclical paths in these problems can indeed be a driving economic force in existing schooling fisheries. In particular, we shall show how the combined effects of increasing marginal returns and the weak dependence of marginal cost on stock lead to collapse in schooling fisheries of species with high reproduction rates, even if they are managed by a sole owner that maximizes present value with a high discount factor. We discuss the consequences and possible solutions of this.

2 Background

The danger of extinction of renewable resources depends critically on the particular form in which the marginal cost of harvesting $c(x)$, as a function of the stock level x, behaves for low stock levels. If $c(x) = cx^{-1}$, where c is constant, and the growth function of the resource is purely compensatory (i.e., strictly concave), extinction is ruled out even for open access fisheries (Gordon, 1954). It is, however, well known that renewable resources are in danger of extinction when exploited in an open access regime (Clark, 1973a). It is also known that open access exploitation may cause both biological and economic inefficiency, since the benefits of an optimal intertemporal allocation of the resource are not considered in open access fisheries.

The above situation can be avoided by a sole owner that maximizes the total net revenues derived from the exploitation of the resource through a discount factor inversely related to the rate of return on alternative investments (discount rates). Clark (1973a, 1973b) showed that, even in this setting and in absence of depensation effects in the population growth dynamics, if the marginal costs are constant, a discount rate in excess of the maximum reproductive rate of the population is a sufficient condition for extinction. Decreasing but still bounded marginal costs will lead to extinction for higher discount rates.

Clark and Munro (1975) showed that, in a context of classical bioeconomic models with marginal costs inversely dependent on stock, an optimal stationary equilibrium x^* exists, and the optimal policy is a "bang-bang" solution: adjust the stock level toward x^* as rapidly as possible. In their model, they divide the marginal return of investment in natural resources into its component parts, on the basis of biological growth and the marginal stock effect (MSE), which measures the marginal return due to the variation of marginal harvesting costs. When MSE attains a significant level for a species, on the order of a discount rate δ, this may translate into an economic force that will rule out the possibility of overfishing. In particular, if the MSE, R, evaluated at the maximum sustainable yield, x_{MSY}, satisfies $\delta = R(< R)$, then the optimal policy preserves the resource from collapse in perpetuity $x^* = x_{MSY}(> x_{MSY})$.

2.1 Danger of collapse of schooling species

Schooling species gather in large banks (schools) which reduce the effectiveness of predators (Clark, 1990; Partridge, 1982). In Mackinson et al. (1997), this characteristic of schooling behavior is modelled through a density-dependent catchability coefficient q of the form $q = ax^{-b}$, where x is the biomass of stock, a is a proportionality constant and b is a parameter with $0 < b \leq 1$ determining the degree to which catchability increases as x decreases. In the reference quoted above, an account is given of the values of the parameter b estimated for various schooling species: See Ulltang (1976) for Norwegian spring spawning herring ($b = 1$), MacCall (1976) for California sardine ($b = 0.611$), Schaaf (1980) for Atlantic menhaden, Shelton and Armstrong (1983) for South Africa sardine, and Csirke (1989) for the Peruvian anchovy ($b = 0.97$). These estimates lead to effort-harvest functions $h = aEx^{1-b}$, with weakened dependence between stock and harvest per unit stock. MSE becomes less important and the survival of the species is endangered by high discount rates or low intrinsic growth rates.

In the cases of the Peruvian anchovy and the Norwegian spring spawning herring, b is close to unity, which gives an (almost) constant catch per unit effort. This is the pure schooling case analyzed by Bjørndal (1988), with harvest function $h = aE$ (constant marginal returns), for the North Sea herring fishery. He showed that stock extinction is "optimal" at high enough discount rates (low discount factor values) $r \geq 0.53$ but, for "reasonable" discount rates $0 \leq r \leq 0.12$, the resource is preserved at an optimal stationary equilibrium.

2.2 Increasing marginal returns: rationale, empirical evidence and difficulties

So far we have discussed the effects of various degrees of dependence of marginal costs from stock level. From this discussion the rule emerges that a weak dependence leads to danger of extinction for high discount rates or low reproduction rates even in the ideal case of a sole owner that maximizes present value. In this research we focus attention on schooling fisheries which combine weak dependence of marginal cost on stock with increasing marginal returns. We shall show that these combined effects may cause collapse in fisheries with both low discount and high reproduction rates. The plausibility of such a situation in fishery management was noticed by Bjørndal and Conrad (1987). They estimated the harvest function for North Sea herring in the pure schooling case as

$$H_t = aE_t^{\alpha}, \tag{1}$$

where H_t is the harvest at period t; a is constant; E_t is the number of participating vessels at period t and $\alpha = 1.4099$. The harvesting costs are given by the concave function $C(H_t) = cE_t = c(H_t/a)^{1/\alpha}$, where c is the variable cost per vessel (Norwegian purse seine) per fishing season.

For a constant unit price of harvest p, the net revenue function from the fishery is in this case the convex function

$$R(H_t) = pH_t - cE_t = pH_t - c(H_t/a)^{1/\alpha}. \tag{2}$$

Therefore, the presence of increasing marginal returns to effort level in (1) gives rise to a nonlinear model in harvesting, which in turn implies decreasing marginal harvesting costs (concave harvesting costs). According to Bjørndal and Conrad (1987), increasing marginal returns linked to the number of boats indicates a positive externality which may be due to boats sharing information about location of schools of herring. Thus, if the size of the fleet increases, the capacity per unit time of the boats required to harvest the most profitable banks of herring increases more than proportionally. This concurs with the observed collapse suffered by this highly prolific species, an occurrence that is more difficult to explain if marginal returns are constant. See also Sterner and Svedäng (2005) for additional arguments in this regard and for details on recent technological advances in information processing that make it easier to find fish schools.

Similar results to those for North Sea herring were found by Bjørndal et al. (1993), for the case of sealing, and Hannesson (1975), for the North Atlantic cod fishery, once among the biggest fisheries in the world and nowadays suffering a dramatic collapse. See Sterner and Svedäng (2005) and Sterner (2007), for further discussion on the collapse of the cod fishery, and Del Valle et al. (2001) for the case of the European anchovy fishery, another collapsed clupeid species.

Notice that the nonlinearity in our model is different from that introduced in Clark and Munro (1975). In their model, nonlinearity is introduced by permitting effort costs $C(E)$ to be nonlinear in effort, which in turn implies that harvesting costs $C(H)$ are nonlinear in harvesting. In particular, they assumed $\partial^2 C(E)/\partial E^2 > 0$, thus implying that $\partial^2 C(H)/\partial H^2 > 0$ (increasing marginal harvesting costs). In this setting, they showed that the optimal approach to an optimal stationary equilibrium is a gradual, asymptotic one.

The existence of cyclical optimal paths in present value optimization of resource management was rigorously proved by Dawid and Kopel (1997) from a theoretical point of view, in a model with convex revenue function and a piecewise linear growth function. They related positively the length of the cycle to the elasticity of the revenue function. Further research by these authors (Dawid and Kopel, 1999) proved that, if the elasticity of the revenue function is high enough and the growth function is smooth and concave, there cannot exist an optimal steady-state path. In that paper, they showed through a numerical experiment that a concave growth function and a concave cost function might give rise to cyclical optimal paths.

The standard assumption on the growth function in the numerical analysis of Dawid and Kopel (1999) left open the possibility that optimal cycles due to increasing marginal returns do exist in actual fisheries[1]. The numerical analysis based on the data of the North Sea herring fishery we describe in Section 3.2 below fully confirms the plausibility of existence of optimal cyclical paths in actual renewable resources management.

In the next section, we describe the North Sea herring fishery and detail the model used in the numerical analysis. We include a discussion of the model's strengths and weaknesses.

3 The optimal management of North Sea herring

North Sea herring is a representative case of a schooling species. In spite of its resilience and ecological value, this species has been driven to collapse by heavy economic exploitation. Indeed, the North Sea herring stock was in danger of extinction in 1977 when a moratorium on fishing had to be imposed due to the overexploitation suffered in the 1970s under an open access regime. In the mid-1990s the North Sea herring stock was in danger of collapse again (ICES, 2005b).

The population dynamics for North Sea herring is given by

$$x_{t+1} - x_t = F(x_t) - H_t, \tag{3}$$

where x_t is the total biomass at the beginning of period t, $F(x_t)$ is the natural growth of the biomass at period t, and H_t is the total catch at period t given by the equation (1). Natural growth is given by the logistic function $F(x_t) = rx_t(1 - x_t/K)$, where r is the intrinsic growth rate and K is the carrying capacity of the environment. This is the standard natural growth function for North Sea herring and it is a suitable approximation to a more complex delay-difference equation (Bjørndal and Conrad, 1987).

It is assumed that the resource is managed by a sole owner whose objective is to maximize the present value of net revenues from the fishery

$$\begin{aligned} &\max_{\{x_{t+1}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t R(f(x_t) - x_{t+1}) && (4)\\ 0 \quad &\leq \quad x_{t+1} \leq f(x_t), t = 0, 1, ..., \\ x_0 \quad &> \quad 0 \text{ given, } R(f(x_t) - x_{t+1}) \geq 0, t = 0, 1, ..., \end{aligned}$$

where R is as defined in (2) and $\beta \in (0, 1)$ is a discount factor. If

$$f(x_t) = x_t + rx_t(1 - x_t/K) \tag{5}$$

in (3) then $f(x_t) - x_{t+1} = H_t$ in (4).

In order to solve Problem (4), we use the following parameters: $p = 1,318$ NOK (Norwegian Kroner) per tonne (source: Norwegian Directorate of Fisheries, 2000); $c = 1,091,700$ NOK (source:

Norwegian Directorate of Fisheries, 2000); $r = 0.53$ (source: ICES, 2002); $K = 5.27$ million tonnes (source: ICES, 2002); $x_0 = 3.591$ million tonnes (source: ICES, 2002); $a = 0.000093769$; $\alpha = 1.4099$; where p is the price in the year 2000 and c is the cost of operating a Norwegian purse seine for one season in the same year. The intrinsic growth rate r and the carrying capacity of the environment K are based on biological data for the period $1981 - 2001$. The initial value of the stock x_0 is from the year 2001. Bjørndal and Conrad (1987) estimated the constant a and the output elasticity of effort α (see Nøstbakken and Bjørndal, 2003 for details on parameter estimation).

Unfortunately, a closed analytic solution of (4) is unattainable, since the required concavity assumptions on which the standard theory rests are not borne out in this situation. This could explain the slow development of research on dynamic programming with discount problems with increasing marginal returns. The standard theory is not able to assess any rate of convergence for the numerical algorithms. Subsequent increases in the discretization grid used in numerical computations can cause significant changes in the outputs. In these conditions, the existence of cyclical optimal policies cannot be rigorously proved by numerical experiments.

We use here the approach described in Maroto and Moran (2005, 2007), where an alternative framework, based on Lipschitz continuity assumptions is proposed. Next, we give a brief description of the numerical algorithm used in the results in Section 3.2.

3.1 Brief description of the numerical algorithm

The solution of (4) with net revenue function (2) and growth function (5) is equivalent (see Stokey, Lucas and Prescott, 1989) to solving the following Bellman equation

$$V(x) = \max_{0 \leq y \leq f(x)} \{R(f(x) - y) + \beta V(y)\}. \tag{6}$$

Notice that Problem (6) can be expressed in terms of finding the fixed point of Bellman operator T defined, for $V \in C(X)$, by

$TV(x) = \max_{0 \leq y \leq f(x)} \{R(x, y) + \beta V(y)\}$, where $C(X)$ denotes the space of bounded continuous functions with the supremum norm. Computing this fixed point involves two steps: a) A discretization T_δ of T as an operator that acts on real functions defined on a discretization grid of the phase space $[0, K]$ of diameter δ; b) The fixed point V_δ of T_δ is then obtained through the iteration of T_δ. The convergence of V_δ to the true value function V of the true Bellman operator T is proved in Maroto and Moran (2007) with a rate $O(\delta)$ of convergence. The only requirement is that R and f in (6) are Lipschitz continuous functions, i.e, mappings under whose action the distance between any pair of points in its domain of definition only can increase by a bounded factor. The broad class of continuous, piecewise differentiable functions with bounded derivative satisfies this condition without any additional requirement on their concavity, so the numerical convergence of the algorithm described above is guaranteed for standard dynamic programming problems under smoothness assumptions alone.

3.2 Numerical results

All data in the example below were generated using a Compaq AlphaServer GS160 6/731 ALPHAWILDFIRE Computer, coded in standard FORTRAN 77. The stock levels in all numerical proofs have been normalized, taking the carrying capacity K as unity.

Results in Table I, columns II, III and IV and Figure 1 correspond to the solution of Problem (4) for different discount factor values. This is the case of sole ownership that does not take into account the Precautionary Approach (PA) endorsed by the ICES (ICES, 2005a) because lower bounds established to preserve the stock are not imposed by the sole owner.

In this case, there is a strongly attractive optimal cycle to which the optimal policy converges instantaneously, due to the horizontal branch of the optimal policy graph (Figure 1).

Figure 1 represents the optimal policy correspondence and the optimal policy dynamics (without PA) for a discount factor $\beta = 0.94$. We can see in this figure that the optimal policy correspondence coincides with the growth function of the resource f at low stock (normalized) levels $x \in [0, \bar{x}]$, with $\bar{x} \simeq 0.569$. We can also observe in this figure the strongly attractive period-five cycle traced for $t = 2001$ from the initial stock level $x_0 = 3.591/5.27 = 0.68$.

Columns II, III and IV in Table I summarize relevant information on the optimal policy of a sole owner without PA. Biological extinction of the resource occurs for discount factor factors $\beta \leq 0.71$ (discount rates $r \geq 41\%$). The lowest stock of the cycle $x_{\min}$ is less than the minimum spawning stock biomass benchmark $B_{\lim} = 0.15$ (800000 tonnes), proposed by ICES (ICES, 2005a), for discount factor $\beta \in [0.72, 0.85]$ (discount rates range from 18% to 39%). The stock is outside safe biological limits[2] for high discount factor values $\beta \in [0.86, 0.94]$ with $B_{\lim} < x_{\min} < B_{pa}$, where B_{pa} is the precautionary approach reference point proposed by ICES (ICES, 2005a). For instance, we can see in Fig. 1 that $x_{\min} = 0.2$ (1 million tonnes) is less than $B_{pa} \simeq 0.25$ (1.3 million tonnes) for a discount factor $\beta = 0.94$.

Notice that the North Sea herring fishery was closed for four years staring at the end of 1977 to allow a stock recovery. We obtained a five cycle period as a result for discount factor levels $\beta \in [0.85, 0.94]$ (see Table I). This can be thought of as an empirical validation on the adequacy of the growth law used in our numerical simulations: Optimal policies obtained from these parameter values provide almost the same results as the implementation of a moratorium.

Thus, our numerical experiments show that a renewable resource with a high rate of growth (rate of return on the resource at zero stock size $r = 0.53$), managed by a sole owner that does not take into account the PA, might be in danger of collapse even for high values of the discount factor $\beta \in [0.85, 0.94]$ because cyclical optimal policies drive the resource below B_{pa}. Only for discount factors higher than 0.94, fairly above those currently applied by economic agents, the stock remains inside safe biological levels.

Results in Table I, columns V, VI and VII, correspond to the solution of Problem (4) for different discount factor values, with the additional constraint, according to the PA, $x_t \geq B_{pa}, t = 0, 1, 2....$

PA is endorsed in order to avoid actual stocks to fall below $B_{\lim}$. If at some period $B_{\lim} < x_t < B_{pa}$, a moratorium is imposed until the prescribed minimum level B_{pa} is attained.

The value of the problem in this case is similar to that obtained in the case of sole ownership that does not take into account PA. The lowest stock of the cycles coincides with the biomass precautionary approach reference point, $x_{\min} = B_{pa} \simeq 0.25$, for discount factors $\beta \in [0.71, 0.95]$. We can also observe in Table I that there is a moratorium (three periods of null harvest for discount factors $\beta \in [0.85, 0.95]$, and two periods of null harvest for $\beta = 0.71$) followed by a big harvest. Thus, if the sole owner takes into account PA, then the resource remains inside safe biological limits.

Table II shows the solution of (4) with PA for a discount factor $\beta = 0.9$ and different values of B_{pa}. Management based on the PA seeks to be risk averse because spawning biomass and fishing mortality can only be estimated with uncertainty. Safe biological limits estimated by ICES take into account this issue (ICES, 2005a). Because B_{pa} is a mechanism for managing the risk of the stock falling below $B_{\lim}$, the distance between these reference points is not fixed but will vary with the assessed amount of risk that society is prepared to bear. Results in Table II show that if B_{pa} increases (80%) then the resource is preserved at a high level, $x_{\min} = 0.447$ (2.35 million tonnes), with proportionally small losses of its present value (15%). This optimal policy is achieved through a more regular harvesting plan that reduces the moratoria periods, increasing the regularity of harvesting by reducing the period of the optimal cycle (period-two cycle), reducing mooring costs. Thus, management based on higher risk aversion to stock collapse can preserve the resource without big losses to its present value, as shown by the small elasticity B_{pa}-present value (-0.168), for the current B_{pa}. Such elasticity exhibits small variability over a significant range of B_{pa} (if B_{pa} proposed by ICES increases (40%) then the elasticity ranges from -015 to -0.26).

4 Discussion of the results

The incorrect assumption of decreasing marginal returns may be misleading if used to establish confidence about the market alone, perhaps with the help of changes in the allocation of property rights, in order to guarantee sustainability and intergenerational equity. Danger of collapse exists even under ideal conditions such as healthy growth rates of resources, the highest degree of centralization (sole owner), and demonstrated concern for future social welfare (high discount factor). Weaker forms of centralized property rights through shared ownership, like common management, should give poorer results from the point of view of sustainability, since any weakening of the sole ownership creates incentives for surpassing the assigned catches.

Increasing marginal returns put intergenerational equity in a dichotomized situation. If, as is the case in our numerical analysis, the length of an optimal cycle is short with respect to the life span of the individuals and the cycle is adopted without a relevant delay, then intergenerational fairness is always guaranteed, independently from the concept of fairness that one wishes to consider. But if the present value optimization pushes the resource to extinction, the most extreme form of inequity between generations might occur.

With regard to sustainability, the existence of significant increasing marginal returns might create a permanent danger of collapse or depletion of renewable resources, periodically driving the stocks near or below the safe biological limits established by the PA, or by the Safe Minimum Standards in the case of other renewable resources. This could be, of course, a form of intergenerational inequity: if future generations could give their opinion, it is not probable that they would applaud the present danger to future stocks caused by current overexploitation. Only unrealistically high discount factors can prevent this danger.

Centralized property rights together with a strict observation of the PA can achieve sustainability and intergenerational equity without a significant loss of the present value of economic exploitations. In this setting, optimal policies tend, however, to drive cyclically the resources to the precautionary lower limit. Thus, adhering to Safe Minimum Standards implies a state of permanent tension. Collapsed stocks can be avoided if regulatory agencies are endowed with full enforcement power and they apply PA based on higher social risk aversion criteria. Cost-benefit analyses of increased current values of B_{pa} for species with prominent roles in the trophic chain are in order.

There is some empirical evidence that the most successful management strategies are based on a combination of suitable property rights and steady application of the PA. The United States has imposed an all-encompassing legal approach (the Magnusson-Stevens Act) on fisheries management and recovery plans have successfully raised fish stocks (Sterner and Svedäng, 2005). Our numerical analysis of the North Sea herring fishery seems to confirm that increasing marginal returns follow the same pattern.

The logical conclusion is that institutional help is needed in order to correct the externalities inherent to consumption of natural resources. Safe biological limits, as prescribed by the PA, must be imposed and carefully verified, taking into account the precarious situation of fisheries at the moment and uncertainty about how pollution and global climate change will affect the whole ecosystem.

5 Extensions and future research

Some issues are left open to future research.

i) Cyclic optimal policies of schooling species, like North Sea herring, which play a crucial role in the ecological system, can cause unpredictable ecological damage. Research efforts should be devoted to the evaluation of such damage weighed against the economic loss implied by higher precautionary reference points. The case of the North Sea herring suggests that the precautionary reference points established in this fishery might be too low, even if (or, perhaps, because of) they are being systematically surpassed. According to the ICES, the probability for the stock to be below B_{pa} in 2008 is about 0.74 and the probability for the stock to be below $B_{\lim}$ in 2008 is 0.2 (ICES, 2005b).

ii) The model for the North Sea herring fishery presented in Section 3.2 should be improved by considering a stock dependent harvest function and the mooring costs of an oversized fishing fleet. A stock dependent harvest function should reduce overfishing, while mooring costs and a backward bent offer curve would have the opposite effect, if endogenous prices were considered. Thus, it is difficult to determine the result of adding these factors to the model. In any case, the results of this paper do not depend critically of the non-stock dependence of the harvest function in equation (1). Further numerical experiments using $H_t = 0.06157 E_t^{1.3556} x_t^{0.5621}$ (see Bjørndal and Conrad, 1987), give qualitatively equivalent results to those described above. This shows that the results of our research extend to schooling fisheries with a catchability coefficient $q = ax^{-b}$, $b < 1$ (non pure schooling case).

iii) Research is needed in order to give a theoretical basis to equation (1), or more in general, to decreasing marginal cost functions and obtain sharper analytic results on non concave problems of dynamic programming with discount. A mathematical analysis of the problem is not beyond reach. However, the analysis is complex because the geometric and dynamic aspects of optimal allocations of boats must be carefully examined. From a more general point of view, cooperation is admittedly a source of decreasing marginal costs. A combination of the technologic and the biological characteristics of schooling species, creates incentives for high cooperative efficiency which, in turn, weakens the marginal stock effect. At low stock levels, with high reproductive rates, full inversion becomes optimal. Danger of collapse can, however, appear preceded by seemingly safe situations of high stock levels, when the reproductive rate falls and big harvests become optimal. Research is needed to explore how uncertainty in current stock measurement might increase the danger of collapse at high stock levels (see Clark and Kirkwood, 1986).

Of particular interest are the horizontal branches in the optimal policy correspondence (see Figure 1) that cause the almost instantaneous convergence with an optimal cyclic path. This might be a universal feature of increasing marginal returns (see Maroto and Moran, 2005; Dawid and Kopel, 1997).

iv) Research is needed in order to clarify the concept of fairness that society wishes to apply under the spectre of increasing marginal returns, which in turn implies a consideration of alternative approaches regarding the discount factor. See Berman and Sumaila (2006) for how empirical research might contribute to determine the proper discount rate if the amenities that restored ecosystems produce are taken into account in utility functions. See also Gowdy (2004) (hyperbolic discounting), Weitzman (2001) (gamma discounting), and Sumaila and Walters (2005) (intergenerational discounting) for specific alternatives to a fixed periodic discount rate.

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Notes

1.− However, the cost function they used to obtain a convex revenue function, of the form $C(h) = bh(2 - h)$, with b a constant and h the catch, implies a null marginal cost when h takes its maximum possible value at $h = 1$, a somewhat extreme hypothesis.

2.− The data used to estimate the growth function are on total biomass – not on spawning biomass. The spawning biomass is (according to ICES) much smaller than total biomass. In our comparison of biomass from our model and the minimum spawning stock biomass benchmark $B_{\rm lim}$ (given by ICES), the low $x_{\min}$ value is therefore even more dramatic (we would like to thank L. Nøstbakken for this comment).

Figure caption

Figure 1

The optimal piecewise discontinuous policy correspondence and optimal policy dynamics solutions of (6) for discount factor $\beta = 0.94$. Observe the optimal plan, convergent to the attractive period-five cycle traced for $t = 2001$ from the initial stock level $x_0 = 0.68$.

Table I

Numerical results for reasonable discount factor levels β∈[0.71, 0.95]

β	$x_{\min}^{NPA}$	Period of the cycle (NPA)	$V_{NPA}(x_0)$	$x_{\min}^{PA}$	Period of the cycle (PA)	$V_{PA}(x_0)$
0.71	0	extinction	3.349	0.246	3	2.8
0.85	0.138	5	4.228	0.253	4	4
0.9	0.2	5	5.585	0.253	4	5.55
0.94	0.2	5	8.474	0.253	4	8.447
0.95	0.253	4	9.842	0.253	4	9.806

The value $x_{\min}^{NPA}$ is the lowest stock of the cycle (million tonnes) in the optimal policy dynamics in the case of sole ownership that does not take into account the Precautionary Approach (NPA). $V_{NPA}(x_0)$ (thousand million NOK) is the net present value in the case of sole ownership that does not take into account the Precautionary Approach. $x_{\min}^{PA}$ and $V_{PA}(x_0)$ (thousand million NOK) are the same values in the case of sole ownership that takes into account the Precautionary Approach (PA).

Table II

Numerical results in the case of sole ownership that takes into account the Precautionary Approach for a discount factor β=0.9 and different values of B_{pa}

B_{pa}	x_{min}	Period of the cycle	$V(x_0)$
1.3	0.253	4	5.55
1.43	0.277	4	5.47
1.56	0.3	3	5.398
1.69	0.32	3	5.341
1.82	0.353	3	5.259
1.95	0.374	3	5.145
2.08	0.4	3	5.027
2.21	0.419	3	4.902
2.31	0.438	3	4.76
2.32	0.447	2	4.723

The value B_{pa}=1.3 million tonnes is the current biomass precautionary approach reference point proposed by ICES. $V(x_0)$ (thousand million NOK) is the net present value.

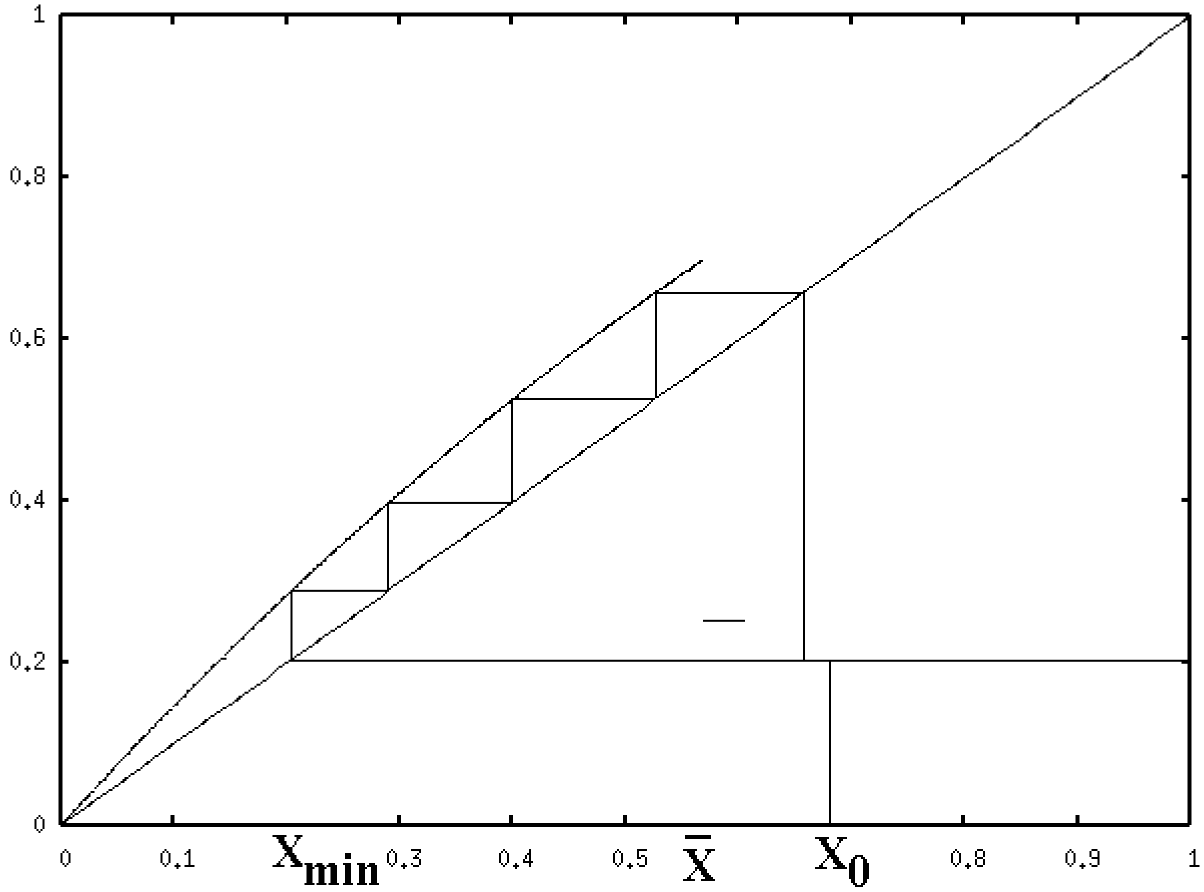

Figure 1. Optimal policy correspondence and optimal dynamics