

STOCHASTIC FEEDBACK POLICIES UNDER ALTERNATIVE MANAGEMENT REGIMES

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ABSTRACT

A discrete-time stochastic bioeconomic model is developed and used to analyse the North Sea herring fishery under alternative management regimes. The analysis focuses on how catches and harvesting policies change with the price of herring. Two production functions are used to explain the harvesting process. At small stock levels, the choice of production function is seen to be critical for the model's predictions. Feedback policies are found for the optimally managed fishery. The management of North Sea herring, after a moratorium was lifted in 1981, is evaluated with respect to effects on supply, stock level, and fishing effort. Under optimal management, the results imply that the fishery should have stayed closed until 1983, a conclusion that is independent of harvesting relationship used. Whether open access leads to total depletion or not is seen to depend on the choice of production function.

Keywords: Fisheries management; Feedback policies; Bioeconomics; Renewable resources; North Sea herring

INTRODUCTION

In most bioeconomic models, price is assumed fixed. This is a simplifying assumption that is often made when analysing the optimal exploitation of a renewable resource. The aim of this paper is to investigate and quantify how the harvesting of fish varies with price under different regulations. Such knowledge is important with respect to analysis of the fishery under optimal management, open access, and other regulatory regimes. Nøstbakken and Bjørndal [1] derived and estimated supply curves for the North Sea herring fishery. Apart from this, there are few empirical applications of supply functions in the literature. In Nøstbakken and Bjørndal's analysis, a deterministic bioeconomic model was used. While the deterministic case offers some useful benchmarks, there are many sources of uncertainty that influence real-world fisheries. In this paper, a stochastic bioeconomic model will be used to analyse the North Sea herring fishery under different management regimes. The current analysis will, to some degree, be an extension of the work in Nøstbakken and Bjørndal [1].

Two different production functions will be used to explain the harvesting of North Sea herring. While the analysis will show that the difference between the two under optimal management is small, the choice of the harvesting relationship has big implications for the predictions made for the fishery under open access. For the open-access case, we find that the choice of production function is crucial for predicted harvest when the stock level is low, even though the two production functions give similar predictions for higher stock levels.

The optimal management of North Sea herring was analysed by Bjørndal ([2], [3]). His analyses are based on deterministic models of the fishery. By including uncertainty in the bioeconomic model, we might get further insight into the optimal management of a pelagic fishery such as that for the North Sea herring. In our stochastic setting, we will find feedback policies for the optimally managed fishery. Optimal feedback policies will depend on the stock level, but also on the price of herring. In an attempt to evaluate how efficient the management of the North Sea herring has been, the optimal feedback policies will be applied to the fishery for the period 1981-2001.

The paper is organised as follows. In the next section, a description of the North Sea herring fishery will be given, and a bioeconomic model will be presented and estimated. In section 3, numerical analyses are undertaken. The final section summarises and concludes.

BIOECONOMIC MODEL AND EMPIRICAL ANALYSIS

The first part of this section gives a short overview of the North Sea herring fishery. The second part presents the bioeconomic model, while parameter values for the model are estimated in the third part.

The North Sea herring Fishery^a

The North Sea autumn spawning herring (*Clupea harengus*) is a pelagic stock that lives on plankton. The stock was severely depleted in the 1960s and 1970s due to overfishing under an open-access regime combined with the development of very effective fish-finding technology [3]. In 1977, the fishery was closed to allow the stock to recover. Since the moratorium was lifted, regulations have been in effect. Nevertheless, in the mid-1990s the stock once again was below safe biological limits,^b and in 1996 the total quota was reduced to save the stock from collapse. To rebuild the stock, the quotas have been relatively small from 1996 onwards. Recent stock estimates show that it has been rebuilt above the level that guarantees good recruitment [4]. While the total quota was held constant from 1999 to 2002, the quota increased with about 40 percent from 2002 to 2003. The North Sea herring has been considered a common resource between Norway and the European Union (EU) after the introduction of extended fisheries jurisdiction (EFJ).

The Model

Reed's [5] stochastic stock-recruitment model is used. The Reed model is an aggregated model and uncertainty is included in a way that makes the model tractable. The model can be written as follows:

$$X_{t+1} = z_{t+1} G(S_t) \quad (\text{Eq. 1})$$

$$S_t = X_t - Y_t, \quad (\text{Eq. 2})$$

where X_t is the total biomass at the beginning of period t , S_t is escapement, and Y_t is harvest. z_{t+1} are independent and identically distributed random variables with mean one and constant variance, observed at the beginning of period $t+1$. $G(S_t)$ is a growth function.

z_{t+1} can be thought of as environmental shocks that occur between last period's harvest and the current period's recruitment. The fishery manager can thus set the quota at the beginning of every period, after the uncertainty has been revealed. In most real-world fisheries, fisheries managers do not know the exact stock level when setting quotas. Clark and Kirkwood [6] deal with this by modelling a fishery with a model similar to Reed's, but where the uncertainty is revealed after the harvest level has been determined. With this specification, they show that the optimal harvesting policy is different from the optimal policy in the Reed model. Weitzman [7] also uses a model similar to Reed's, but where regulatory decisions are made before the period's recruitment is known. He uses his model to compare different management instruments.

The Reed model seems to give a reasonable representation of the growth in the North Sea herring stock, as we shall see in the next section where the empirical analysis is described.

It is assumed that harvest in period t is given by an industry production function:

$$Y_t = H(K_t, X_t) \quad (\text{Eq. 3})$$

This function relates harvest, Y_t , to effort, K_t , and stock size, X_t . According to Bjørndal and Conrad [8], search for schools is of predominant importance in a fishery on a schooling species like herring. Thus, in such fisheries the number of participating vessels may be an appropriate measure of effort, an assumption that will be made throughout this paper.

By assuming a constant cost per unit effort, the net revenue for the industry can be written as $p_t = pY_t - cK_t$, where p is the price per unit of harvest and c is the unit cost per vessel per season.

Production Functions and Optimal Harvest

Two forms of the aggregate production function in (Eq. 3) will be considered, the Spence [9] and the Cobb-Douglas production functions. In this section, these relationships and their optimal feedback policies are presented.

In the Reed [5] paper, the Spence harvesting function is used:

$$Y_t = X_t (1 - e^{-qK_t}), \quad (\text{Eq. 4})$$

where $q > 0$ is a catchability coefficient. We see that $Y_t \rightarrow X_t$ as $K_t \rightarrow \infty$ and it is thus very difficult to harvest the stock to total extinction in this model.

It is easily shown that net revenues are as follows:

$$p_t = pY_t - \frac{c}{q} [\ln(X_t) - \ln(S_t)]. \quad (\text{Eq. 5})$$

As Reed [5] noted, this can be written as an additive separable function of the state variable, X , and the control variable, S . We then have $p_t = N(X_t) - N(S_t)$, where $N(m) = pm - \frac{c}{q} \ln m$.

In an optimally regulated fishery, we assume that a sole owner or a social planner, whose objective is to maximise the expected value of discounted net revenues from the fishery, manages the fish stock. He thus faces the following maximisation problem:

$$\max_{\{S_t\}} E_0 \left[\sum_{t=0}^T r^t \{N(X_t) - N(S_t)\} \right] \quad (\text{Eq. 6})$$

subject to (Eq. 1), (Eq. 2), and X_0 given. $r = 1/(1+d)$ is the discount factor, and d is the discount rate. The maximisation problem can be solved using stochastic dynamic programming. It can be shown that the optimal harvest policy is a constant-escapement policy where the optimal escapement level must maximise the following equation:^c

$$W(S) = rE_z [N(zG(S))] - N(S) \quad (\text{Eq. 7})$$

This equation can be solved numerically for the optimal escapement level, S^* . The optimal policy can be expressed as:

$$Y_t = \begin{cases} (X_t - S^*) & \text{if } X_t > S^* \\ 0 & \text{otherwise} \end{cases} \quad (\text{Eq. 8})$$

Let us now turn to the Cobb-Douglas production function, which can be expressed as:

$$Y_t = aK_t^b X_t^g \quad (\text{Eq. 9})$$

The parameter a in this relationship represents the efficiency of the fishing fleet. The parameters b and g are the output elasticities of stock size and effort, respectively.

As opposed to the Spence function, effort does not have to approach infinity as $Y_t \rightarrow X_t$ for the Cobb-Douglas production function. It is consequently possible to drive the stock to zero without having an infinite number of vessels participating in the fishery.

Net revenues are given by the following equation:

$$p_t = pY_t - c \left(\frac{Y_t}{aX_t^g} \right)^{\frac{1}{b}} \quad (\text{Eq. 10})$$

In an optimally regulated fishery, the manager would want to maximise the expected value of discounted net revenues from the fishery. Unfortunately, it is not possible to express net revenue as a separable function of the state variable and the control variable when we use the Cobb-Douglas function. This means that we cannot derive a closed-form solution for the optimal harvest policy.

Instead of solving the maximisation problem analytically, we will use numerical analysis to find an optimal feedback policy. The feedback policy can be specified in an infinite number of ways and we do not know the form of the optimal policy. The current analysis will therefore be restricted to finding an optimal *linear* feedback policy, given by the following equation:

$$Y_t = \mathbf{a} + \mathbf{b}X_t \quad (\text{Eq. 11})$$

In Pindyck's [11] continuous-time models, linear feedback policies emerge in three examples. Our search for optimal linear feedback policies thus seems fairly reasonable, although there might exist non-linear policies that would outperform the linear policies.

Harvest in any year can for obvious reasons never exceed the total biomass. In most fisheries it is also impossible to have a negative harvest. We therefore add the restriction $0 \leq Y_t \leq X_t$, that must hold for all t . The upper boundary condition for Y_t is not expected to be binding, since total extinction of a fish stock with an intrinsic growth rate as high as the herring's is very seldom optimal. With these restrictions on Y_t , the optimal feedback policy we are searching for is not strictly linear.

Vessel Dynamics

In accordance with Gordon [12], it will be assumed that vessel entry and exit under open access follows the sign and size of net revenues per vessel. Fleet dynamics are assumed to occur according to the following equation:

$$K_{t+1} - K_t = n \frac{P_t}{K_t}, \quad (\text{Eq. 12})$$

where $n > 0$ is an adjustment parameter. If net revenue per vessel is positive, effort will increase. If net revenue per vessel is negative, effort will decrease.

In the optimally regulated fishery, we assume that the optimal number of vessels will participate in the fishery every year. Consequently, there will be no transition period if the optimal number of vessels changes from one season to the next. This is a simplifying assumption that implies that vessels becoming redundant in the North Sea herring fishery immediately will be needed and employed in other fisheries. The question of optimal fleet size is more complicated and calls for a joint analysis of all fisheries in which the fishing fleet participates. Nevertheless, being relatively minor compared to other fisheries, the North Sea herring fishery's influence on the optimal fleet size is modest.

Empirical Analysis

The empirical content of the model consists of the specification and estimation of the stock-recruitment function, and of the production and cost functions.

Stock-Recruitment Function

A specification of stock-recruitment corresponding to the deterministic part of (Eq. 1) is given by the following logistic function:

$$X_{t+1} = G(S_t) = S_t \left(1 + r - \frac{rS_t}{L} \right), \quad (\text{Eq. 13})$$

where r and L represent the intrinsic growth rate and carrying capacity of the stock, respectively [13]. This equation was estimated by ordinary least squares using annual data on total biomass and harvest for the North Sea herring for the period 1960-2002 obtained from the International Council for the Exploration of the Sea (ICES).^d Parameter estimates are presented in Table I.

The estimated equation was tested for autocorrelation and the test statistics indicated that first-order autocorrelation might be a problem. The Durbin-Watson test statistic is reported in Table I. In the remainder of the paper, we will use parameter estimates corrected for first-order autocorrelation using the Cochrane-Orcutt transformation (lower panel, Table I).

Table I. Estimates of the Parameters of the Stock-Recruitment Function

Parameter	Coefficient	Standard Error	t value
r	0.432	0.075	5.76
L	6,677,528	1,549,772	4.31
$R^2 = 0.989$; $adjR^2 = 0.988$; $DW = 1.319$			
<u>Auto</u>			
r	0.462	0.093	4.95
L	5,713,479	1,168,269	4.89
$R^2 = 0.980$; $adjR^2 = 0.979$; $DW = 2.060$; $r = 0.298$			

According to the regression results, the escapement level that maximises annual sustainable harvest is $S_{msy} = L/2 = 2,856,740$ tonnes. The corresponding maximum sustainable yield and biomass are $MSY = rL/2 = 660,335$ tonnes and $X_{msy} = (L/4)(2+r) = 3,517,075$ tonnes.

Estimated growth functions for herring can be found in several papers. Bjørndal [3] and Nøstbakken and Bjørndal [1] estimate growth functions for North Sea herring using data for the period 1947-1981 and 1981-2001, respectively. Arnason, Magnusson, and Agnarsson [14] estimate a growth function for Norwegian spring-spawning herring using data for the period 1950-1995. However, in these papers it is assumed that growth is determined by biomass, X_t , not by escapement, S_t , as in the model estimated here. The three papers mentioned above report intrinsic growth rates of 0.52, 0.47, and 0.53, respectively. Our estimate of intrinsic growth rate, as reported in Table I, thus seems to be robust. In addition, all the estimated parameters presented in Table I are significant at a 5% significance level, and the estimated equation explains over 98% of the variation in the data. Modelling the growth as a function of escapement as opposed to biomass at the beginning of the period seems to result in a higher adjusted R^2 when estimating recruitment in this fishery. Bjørndal's [3] estimate of carrying capacity for the North Sea herring is a *spawning stock* of 3.55 million tonnes, while Nøstbakken and Bjørndal [1] reports a *total stock* of 5.27 million tonnes. In comparison, our estimate seems reasonable.

The model assumes that the mean of z_{t+1} is one. Unless otherwise stated we will make the additional assumptions that the variance of z_{t+1} is $\sigma_z^2 = 0.05$ and that z_{t+1} is log-normally distributed.^e

Vessel Dynamics, Production Functions, Costs, and Prices

Bjørndal and Conrad [15] analyse capital dynamics in the North Sea herring fishery. They estimate several fleet-adjustment equations but unfortunately not (Eq. 12). Data presented in [8] and [15] are therefore used to estimate the adjustment parameter n in (Eq. 12).^f OLS estimation gives us a point estimate of $n = 10^{-4}$.

Bjørndal and Conrad [8] estimated four production functions based on data for Norwegian purse seine vessels in the North Sea herring fishery, 1963-1977. The two functions that best fit the data, along with Bjørndal and Conrad's parameter estimates, are used in the current analysis.^g These are the Spence production function (Eq. 4) with $q = 0.0011$, and the Cobb-Douglas production function (Eq. 9) with $a = 0.06157$, $b = 1.356$, and $g = 0.562$.

Following Nøstbakken and Bjørndal [1], cost data for Norwegian purse seine vessels with cargo capacity 8,000 hectolitres and above is used in the analysis. See Nøstbakken and Bjørndal [1] for details on cost and price estimation. All prices and costs are in nominal NOK. For 2001, the adjusted average price is 2,465 NOK/tonne, and variable cost per vessel is 1,189,565 NOK/year. A 6% discount rate is used in the analysis.

THE NORTH SEA HERRING FISHERY

In this part, optimal management of the North Sea herring fishery is analysed by using the two production functions. Stochastic simulations are used in the analysis. All simulations were programmed and run in MATLAB.

Model 1: The Spence Production Function

By stochastic simulations, the optimal escapement level can be found for given price, cost, and discount factor. Figure 1 shows the relationship between optimal escapement level and price for different values of s_z^2 . The optimal escapement level is not very sensitive to changes in the variance of z_{t+1} . For low prices, the figure shows that there is no difference between the two curves that represent optimal escapement levels for $s_z^2 = 0.05$ and $s_z^2 = 0.20$. As price increases, the difference between the curves grows, but not very much.^h As $p \rightarrow \infty$, the optimal escapement level approaches 2.52 million tonnes ($s_z^2 = 0.05$). The optimal escapement level is thus very insensitive to price changes for prices above $p = 3$ NOK/kg. For prices below 0.2 NOK/kg, the escapement level is higher than the carrying capacity of the environment, L . Consequently, for prices less than 0.2 NOK/kg, there will be no harvesting. By simulating the optimal harvesting rules over a long time period, we can find the statistical distributions of X_t , Y_t , etc.

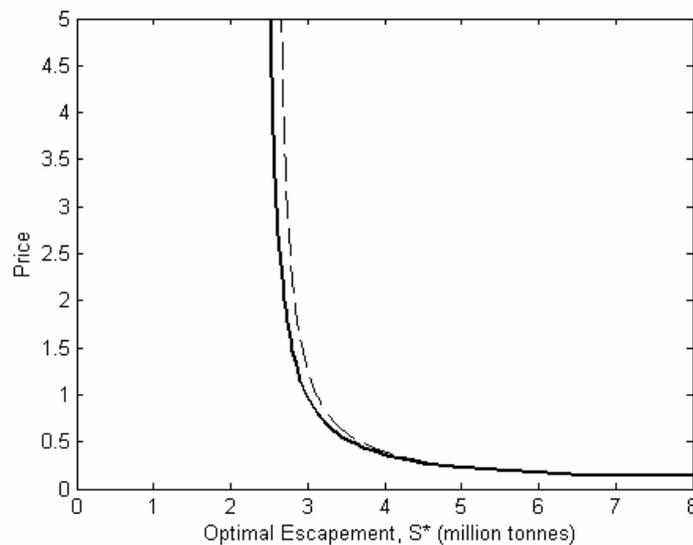


Figure 1. Optimal escapement level, variance $s_z^2 = 0.05$ (--) and $s_z^2 = 0.20$ (c = 1,189,565 NOK, $d = 0.06$)

Model 2: Cobb-Douglas Production Function

Optimal management of the fishery will now be analysed for the Cobb-Douglas production function.

Optimal linear feedback policies (Eq. 11) are approximated for different prices keeping other parameters constant by stochastic simulations. These feedback rules are then applied to the dynamic model of the North Sea herring fishery which are simulated $N = 1,000$ times for $T = 100$ years. Initial biomass is set to L .

If price is too low, i.e., less than about 0.1 NOK/kg, harvesting is not profitable at any stock level and both \mathbf{a} and \mathbf{b} in the linear feedback (Eq. 11) are zero. However, for prices above this level, the optimal linear feedback seems to be rather insensitive to changes in price (and cost). The simulation results show that the optimal \mathbf{b} stays very close to 1, although it decreases with price. Optimal \mathbf{a} increases with price, but the relative change in \mathbf{a} is small. For price $p = 2$, the optimal linear feedback policy is approximately $Y_t = -2,850,000 + 0.99X_t$. For positive values of X_t , harvest will never equal total stock and extinction of the stock is therefore never optimal.

The simulation results for price $p = 2$ shows that the mean values of biomass and harvest after a transition period level out at about 3.5 million tonnes and 654,000 tonnes, respectively. These values are close to the maximum

sustainable yield levels of biomass and harvest. If we, however, look at the simulations separately, we find that the linear feedback rule does not result in a stable annual catch of 654,000 tonnes. Instead, the catch changes from zero in some periods to very high catches in other periods. The linear feedback rule thus appears to lead to pulse fishing in this case.

The North Sea Herring Fishery 1981-2001

In the following sections, Model 1 and Model 2 will be used to simulate harvesting from the North Sea herring fishery, 1981-2001, under open access and optimal management. Average prices and variable costs for these years obtained from the Norwegian Directorate of Fisheries are used. The simulation results will be compared to the actual harvesting policies for the North Sea herring fishery.

Open-Access Dynamics

In this section the models 1 and 2 are used to simulate open-access dynamics of the North Sea herring fishery 1981-2001. Initial biomass in 1981 was, according to ICES, 1,160,300 tonnes. Initial number of vessels is set to 120.

The simulation results from $N=1,000$ simulations show that for Model 2 (Cobb-Douglas) the stock would go extinct after about 10 years (1990). The corresponding prediction when using Model 1 is, as expected, that the stock would not have gone extinct. For this model we see that the number of vessels and harvest decrease steadily until the stock eventually starts increasing again. Full depletion is within one standard deviation from the average stock level from 1996 onwards. For Model 2, the same is true from 1988 onwards.

Figure 2 shows open-access dynamics in terms of number of vessel and stock levels for the two models. By comparing vessel dynamics, we see that the number of vessels reaches its maximum in 1990 for Model 1 and in 1989 for Model 2. Until 1984-1985 the models appear to be somewhat similar. From this point onwards, however, the two models' predictions are quite different. As can be seen in Figure 2, Model 1 and Model 2 follow almost the same path with an increasing number of vessels in the fishery and a decreasing stock, but while it only takes three years in Model 2 to drive the stock down from 1500 to 500 thousand tonnes, this takes about seven years in Model 1.

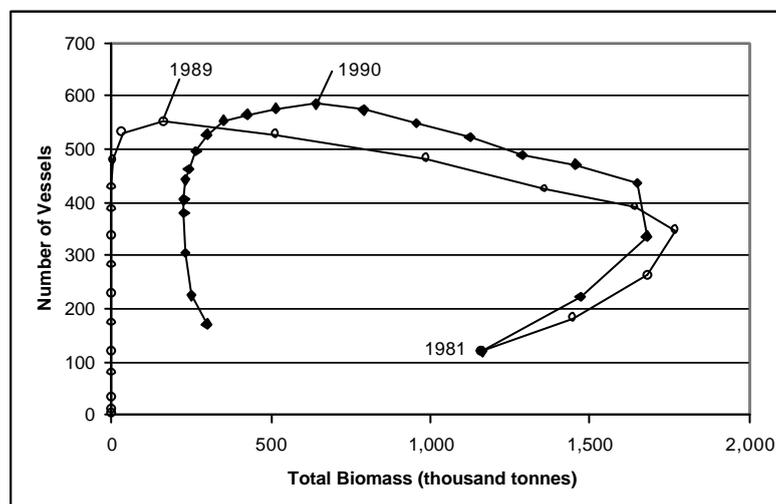


Figure 2. Open-access dynamics, model 1 (Spence) and model 2 (o) (Cobb-Douglas), 1981-2002

To answer the question whether open access could lead to stock extinction, one would get very different conclusions depending on which model specification one uses. Both the Spence and the Cobb-Douglas functions fit the data. It is difficult to say which of the two models offers the best description of harvesting for the North Sea herring fishery. The fishery has not been unregulated since the 1970s.¹ We therefore have no real observations to compare the simulation results to.

The choice of model (Cobb-Douglas or Spence production function) does not have a big impact on predictions if the stock level is not too low. In periods when the stock is at a very low level, however, the two models give very different predictions. The models' predictions for periods when the stock is close to total extinction should therefore be evaluated when determining what production function to use when modelling the North Sea herring fishery. When the North Sea herring fishery was closed in 1977, the stock was at a very low level. It is possible that the moratorium saved the stock from going extinct as put forward by Bjørndal and Conrad [8]. This would suggest that the Cobb-Douglas function best describes the fishery. However, since the stock never has gone extinct, it could very well be possible that the Spence production function gives the best description of harvesting in this fishery.

Optimal Management

We will now compare the performance of the optimal harvesting policies in terms of annual harvest, revenues, etc., to the actual harvesting policy in the North Sea herring fishery 1981-2001. To make this comparison fair, the size of the environmental shock in each period (z_t) is calculated based on the estimated stock-recruitment function and actual stock levels: $z_t = X_t / \hat{X}_t = X_t / G(S_{t-1})$.

In the previous sections, we found that the choice of harvesting relationship used in the bioeconomic model (Spence or Cobb-Douglas) was critical for the predicted open-access dynamics. This, however, does not seem to be important for determining optimal harvest based on actual prices and costs in the fishery for the period 1981-2001. Both annual harvest and stock levels are almost identical between the two models as can be seen in Figure 3. The actual harvest and stock, on the other hand, deviate from these optimal harvesting policies.

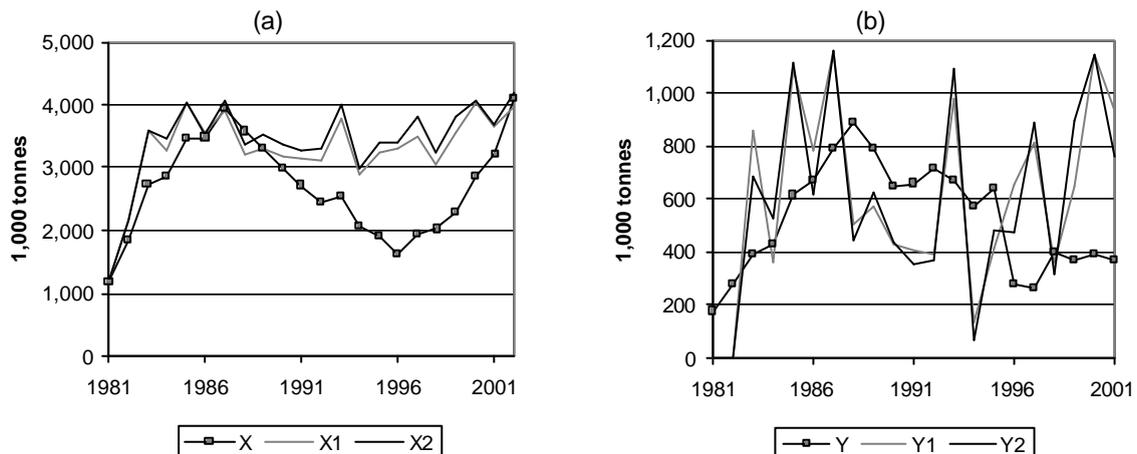


Figure 3. Optimal policies, models 1 (Spence) and 2 (Cobb-Douglas) versus actual policy; (a) stock levels 1981-2002 and (b) annual catches 1981-2001, $d = 0.06$.

According to both our models, optimal management implies that the moratorium should not have been lifted in 1981; the fishery should on the contrary have stayed closed until 1983. This would have rebuilt the stock to a level of some three million tonnes. Both models 1 and 2 level out with a stock at about this level. Remember that the total biomass that corresponds to maximum sustainable yield is about 3.52 million tonnes according to our estimates. Optimal harvest would therefore have been close to the maximum sustainable yield.

Harvest under the optimal management policies fluctuate significantly, with harvests as high as 1,160 thousand tonnes in 1987 and down to a low of 105 thousand tonnes in 1994. These fluctuations follow the fluctuations in z . For Model 1, the optimal escapement level changes some from year to year as prices and costs change. However, the environmental shocks explain most of the fluctuations in optimal harvest ($Y1$ and $Y2$) in Figure 3.

In spite of the fact that total landings were above optimal harvesting levels in the early 1980s, total biomass grew steadily until it reached 3.94 million tonnes in 1987. This is very close to the optimal stock size in 1987. One explanation for this rather large increase in actual biomass is the substantial positive environmental shocks in the early 1980s. From 1987 until 1996, the North Sea herring stock showed a declining trend. During this period the actual harvesting policy was undoubtedly suboptimal. From 1997 onwards, quotas have been small to allow the stock to grow. The stock in 2003 was about 4.32 million tonnes according to ICES [4]. The stock has thus been allowed to grow to a level above the level that maximises net revenues from the fishery.

Figure 4 shows sum of present value of revenues from 1981 onwards for the two optimal harvesting policies and actual harvest.¹ The two optimal harvesting policies derived from the bioeconomic models give almost the same revenues, although the optimal escapement policy for the Spence production function gives marginally higher discounted revenue (Model 1). The gap between the accumulated discounted revenue lines for the two optimal policies is not constant. It increases in some years and decreases in other years. This means that the constant escapement policy performs best in some periods, while the linear feedback policy is best in other periods.

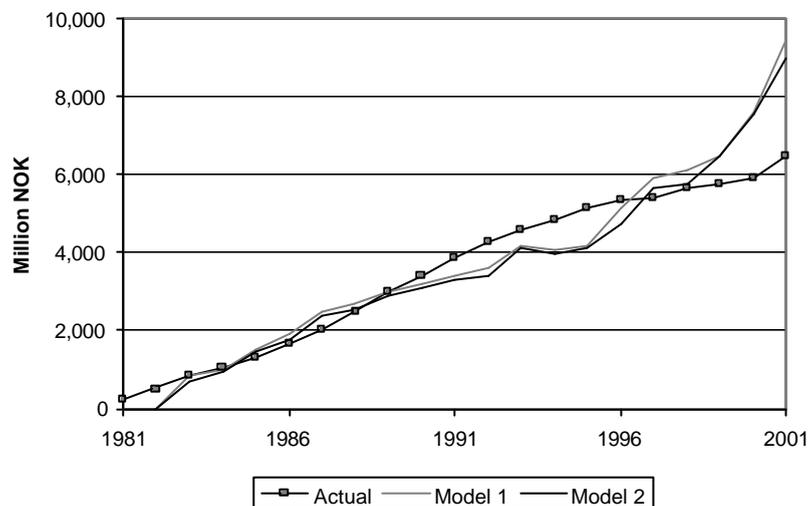


Figure 4. Sum of present value of revenues from 1981 onwards

The actual policy has the highest present value of revenues for the periods 1981 to 1984 and 1981 to 1996. However, while the stock level under optimal management would have been 3.3 -3.4 million tonnes in 1996, the stock level under the actual regulations was only 1.63 million tonnes. It is therefore not correct to say that the actual management (1981-1996) was better than the optimal harvesting policies presented here. Furthermore, for the whole period, 1981-2001, the two optimal harvesting policies clearly outperform the actual management policy. As can be seen in Figure 3, the actual stock level (X) equals the optimal stock levels (X_1 and X_2) in 2002. When comparing present value of revenues from 1981 to 2001, all the three policies; Model 1, Model 2, and actual, have the same initial stock in the first year and virtually the same escapement in the last year. Comparing policies over this period should therefore be reasonable.

The optimal policy for Model 2 (Cobb-Douglas) is, as discussed earlier, the optimal feedback policy among the *linear* feedback policies. The fact that the linear feedback policy gives almost the same results as the optimal escapement policy (Model 1) indicates that our linear feedback probably is close to the optimal policy.

In this section we have seen that the differences in optimal annual harvest levels is very small when modelling the North Sea herring fishery with a Spence production function compared to a Cobb-Douglas production function. This result is contrary to what we found when analysing open-access dynamics. The fact that the two harvesting relationships give so similar recommendations for optimal harvesting of North Sea herring strengthens the robustness of these policies.

SUMMARY AND CONCLUSIONS

In this paper, the North Sea herring fishery has been analysed. A stochastic model was used. When looking at stock-recruitment data for the North Sea herring fishery, it is obvious that there are fluctuations that cannot be explained in the standard deterministic bioeconomic fisheries models. These fluctuations have been treated as independent shocks that occur after harvesting in one period but before determining quotas in the next period.

Two different production functions have been used in the analysis. In an optimally regulated fishery, the Spence production function leads to a constant-escapement rule as proved by Reed [5]. The optimal escapement level was seen to decrease with price. For the model based on the Cobb-Douglas production function, the analysis was limited to finding optimal linear feedback policies for the fishery. We observed that the linear feedback rule can lead to pulse fishing. The optimal policies for the two harvesting functions were seen to be very similar when applying them to the North Sea herring fishery, 1981-2001. This indicates that the optimal feedback policy (Model 2, Cobb-Douglas) probably is not very different from our linear feedback rule. This result also confirms that as long as the stock is not close to total extinction the difference between the two models in terms of expected annual harvest etc. is small.

The North Sea herring fishery was closed in 1977 to allow the stock to recover after being severely depleted in the 1960s and 1970s. The moratorium was lifted in 1981 in the southern part of the North Sea and in 1983 in the northern part. According to our analysis, optimal management of the North Sea herring would have implied that the fishery should have stayed totally closed until 1983. This conclusion is independent of the choice of production function (Cobb-Douglas or Spence).

Our analysis confirms the conclusion made in Nøstbakken and Bjørndal [1] that different regulations can have a substantial impact on the supply of North Sea herring. The difference in long-term expected supply between open access and optimal management depends on the harvesting function used but is nevertheless considerable. Both for the Spence and the Cobb-Douglas function, optimal management results in expected annual landings close to the maximum sustainable yield of 660 thousand tonnes. Under open access, the long term equilibrium stock and harvest can be zero (Cobb-Douglas) or close to zero (Spence). These results are very similar to Nøstbakken and Bjørndal's [1] results for the deterministic case.

This paper represents a continuation of the work in Nøstbakken and Bjørndal [1]. The current analysis can be extended in several ways. One possibility would be to introduce measurement error in the stock estimates (cf. [6]). This would also allow for an analysis of optimal management instruments (cf. [7]), and an analysis of how different management instruments could affect the supply of herring. Another possibility would be to explore implications for optimal management of having autocorrelated instead of independent and identically distributed environmental shocks. The analysis could be extended further by combining the supply curves with estimations of demand curves in order to study the market for North Sea herring.

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ENDNOTES

^a This section is largely based on Nøstbakken and Bjørndal [1].

^b According to the International Council for the Exploration of the Sea, the minimum biological acceptable level is a spawning stock of 800,000 tonnes for the North Sea herring stock.

^c See Conrad [10] for the derivation of this expression.

^d The Gompertz and Ricker functional forms were also estimated. However, the logistic function resulted in the best fit and was therefore chosen.

^e The lognormal distribution ensures that all z values are non-negative.

^f OLS estimation: t -value = 2.08, $R^2 = 0.250$, $adjR^2 = 0.192$, and $DW_{(1,14)} = 1.435$.

^g Bjørndal and Conrad's estimation was for a time period when the fishery was unregulated, and econometric conditions for estimating a production function were satisfied. This would not be the case for later periods, due to varying regulations of the fishery. The implication of using these parameters is that the efficiency of the fleet may be somewhat underestimated due to technological development.

^h The difference in optimal escapement level is about 136,000 tonnes for price $p = 5$ NOK/kg.

ⁱ See Nøstbakken and Bjørndal [1] on regulations of the North Sea herring fishery.

^j The sum of present value of revenues for year t is defined as: $PV_t = \sum_{s=1981}^t (1+d)^{t-s} R_s$, where R_s is net revenue in year s , and d is the discount rate.