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Stochastic Feedback Policies under Alternative Management Regimes

by

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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.

1. 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 (2003) 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 (2003).

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 (1987, 1988). 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.

2. 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.

2.1 The North Sea herring Fishery[1]

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 (Bjørndal 1988). 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,[2] 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 (ICES 2003). While the total quota was held constant from 1999 to 2002, the quota increased with about 40 percent from 2002 to 2003.

After the introduction of extended fisheries jurisdiction (EFJ), the North Sea herring has been considered a common resource between Norway and the European Union (EU). In

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[1] This section is largely based on Nøstbakken and Bjørndal (2003).

[2] 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.

December 1997, the parties agreed on a management scheme for the stock, the EU-Norway agreement, specifying stock objectives and how to set catch quotas. This agreement has been in force since 1 January 1998. According to the EU-Norway agreement, the total quota for the directed fishery shall be allocated between the two parties with 29% to Norway and 71% to the EU. In addition, the EU gets the entire bycatch quota.

2.2 The Model

Reed's (1979) stochastic stock-recruitment model is used. The reasons for this are that it is an aggregated model, and that uncertainty is included in a way that makes the model tractable. The Reed (1979) model can be written as follows:

$$X_{t+1} = z_{t+1} G\left(S_t\right) \tag{1}$$

$$S_t = X_t - Y_t, \tag{2}$$

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 $t+1$. $G\left(S_t\right)$ 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. This means that after observing the random variable in one period, one knows the current period's recruitment level with certainty. 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 (1986) 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 (2002) 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. However, as we noted above, the Reed model assumes that uncertainty is revealed before harvesting policies are set. This is a drawback with this model specification, because the managers do not know the exact level of the North Sea herring stock when setting quotas. The advantage with using Reed's model is that it is much more tractable than, for example, a specification similar to Clark and Kirkwood's (1986).

Further, it is assumed that harvest in period t is given by an industry production function:

$$Y_t = H\left(K_t, X_t\right) \tag{3}$$

This function relates harvest, Y_t, to effort, K_t, and stock size, X_t. According to Bjørndal and Conrad (1987), 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:

$$\pi_t = pY_t - cK_t, \tag{4}$$

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 for the aggregate production function in equation (3) will be considered, the Spence (Spence 1974) and the Cobb-Douglas production functions. In this section, these relationships and their optimal feedback policies are presented.

In the Reed (1979) paper, the Spence harvesting function is used:

$$Y_t = X_t\left(1 - e^{-qK_t}\right), \tag{5}$$

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

The variable cost per unit of fish caught at each point in time can be written as:[3]

$$C = C\left(X_t, Y_t\right) = \frac{c}{q}\left[\ln\left(X_t\right) - \ln\left(X_t - Y_t\right)\right] = \frac{c}{q}\left[\ln\left(X_t\right) - \ln\left(S_t\right)\right]. \tag{6}$$

Net revenue is thus:

$$\pi_t = pY_t - \frac{c}{q}\left[\ln\left(X_t\right) - \ln\left(S_t\right)\right]. \tag{7}$$

As Reed (1979) noted, this can be written as an additive separable function of the state variable, X, and the control variable, S. We then have $\pi_t = N\left(X_t\right) - N\left(S_t\right)$, where $N\left(m\right) = pm - \frac{c}{q}\ln m$.

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:

$$\max_{\{S_t\}} E_0\left[\sum_{t=0}^{T} \rho^t \left\{N\left(X_t\right) - N\left(S_t\right)\right\}\right] \tag{8}$$

subject to (1), (2), and X_0 given. $\rho = 1/\left(1+\delta\right)$ is the discount factor, and δ 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 (Reed 1979), where the optimal escapement level must maximise the following equation:[4]

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[3] $Y_t = X_t\left(1 - e^{-qK_t}\right) \Rightarrow e^{-qK_t} = 1 - Y_t/X_t = \left(X_t - Y_t\right)/X_t \Rightarrow K_t = \left(1/q\right)\left[\ln\left(X_t\right) - \ln\left(X_t - Y_t\right)\right]$

[4] See Conrad (2002) for the derivation of this expression.

$$W(S) = \rho E_z\left[N\left(zG(S)\right)\right] - N(S) \tag{9}$$

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

$$Y_t = \begin{cases} \left(X_t - S^*\right) & if \quad X_t > S^* \\ 0 & otherwise \end{cases} \tag{10}$$

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

$$Y_t = aK_t^b X_t^g \tag{11}$$

The parameter a in this relationship represents the efficiency of the fishing fleet. The parameters b and g are the output elasticity of stock size and effort, respectively. Because of the herrings' schooling behaviour, harvesting can be viable at very low stock levels. The parameter estimate of g is therefore expected to be less than one.

As opposed to the Spence function, effort does not have to approach infinity as $Y_t \to X_t$ 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.

Cost per unit of harvest and net revenue are given by equations (12) and (13):

$$C = c\left(\frac{Y_t}{aX_t^g}\right)^{\frac{1}{b}} \tag{12}$$

$$\pi_t = pY_t - c\left(\frac{Y_t}{aX_t^g}\right)^{\frac{1}{b}} \tag{13}$$

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 do not have a simple way of finding the optimal feedback policy for the fishery.

We cannot solve the maximisation problem analytically and will instead search for an optimal feedback policy among possible policies. 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:

$$Y_t = \alpha + \beta X_t \tag{14}$$

In Pindyck's (1984) 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 $0 \le Y_t \le X_t$, 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 (1954), it will be assumed that vessel entry and exit under open access follows the sign and size of normalised net revenues per vessel. Fleet dynamics are assumed to occur according to the following equation:

$$K_{t+1} - K_t = n \frac{\pi_t}{K_t}, \tag{15}$$

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.

2.3 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 equation (1) is given by the following logistic function:

$$X_{t+1} = G(S_t) = S_t\left(1 + r - \frac{rS_t}{L}\right), \tag{16}$$

where r and L represent the intrinsic growth rate and carrying capacity of the stock, respectively (Clark 1990). This equation was estimated by nonlinear 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).[5] Parameter estimates are presented in Table 1.

The Durbin-Watson statistic given in Table 1 indicates that first-order autocorrelation might be a problem, since the test rejects the null hypothesis of no first-order autocorrelation. The Breusch-Godfrey Lagrange multiplier test of autocorrelation of order P was used to test the logistic equation for autocorrelation of order $P \in [1,5]$. The null hypothesis of no autocorrelation was rejected for $P = 1$ (5 % significance level). For $P > 1$, the null hypothesis could not be rejected.

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

Table 1. Estimates of the Parameters of the Stock-Recruitment Function.

Parameter	Estimated Coefficient	Standard Error	t value
	NLS		
r	0.462	0.075	5.76
L	6,677,528	1,549,773	4.31
	$R^2 = 0.989$; $adj.R^2 = 0.988$; $DW = 1.319$		
	OLS-Auto		
$\beta_1 = 1 + r$	1.462	0.093	15.67
$\beta_2 = -r/L$	$-8.09 \cdot 10^{-8}$	$3.14 \cdot 10^{-8}$	-2.58
	$r = 0.462$; $L = 5,713,479$		
	$R^2 = 0.980$; $adj.R^2 = 0.979$; $DW = 2.060$; $\rho = 0.298$		

Table 1 also presents the regression results from estimating the logistic function using the Cochrane-Orcutt transformation to correct for first-order autocorrelation. After the correction, the point estimate of the carrying capacity is smaller while the estimated growth rate is nearly unchanged. The Durbin Watson test statistic implies that there is no first-order autocorrelation after the transformation. In the remainder of the paper, we will use the parameter estimates corrected for autocorrelation.

According to the regression results, the intrinsic growth rate of the biomass is $r = 0.46$ and the carrying capacity of the environment is $L = 5,713,480$ tonnes. The escapement level that maximises annual sustainable harvest is thus $S_{msy} = L/2 = 2,856,740$ 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 (1988) and Nøstbakken and Bjørndal (2003) estimate growth functions for North Sea herring using data for the period 1947-1981 and 1981-2001, respectively. Arnason, Magnusson, and Agnarsson (2000) 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. Our estimate of intrinsic growth rate should therefore be somewhat smaller. 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 1, thus seems to be robust. In addition, all the estimated parameters presented in Table 1 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 (1988) estimate of carrying capacity for the North Sea herring is a *spawning stock* of 3.55 million tonnes, while Nøstbakken and Bjørndal (2003) 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.[6] Ideally, we should estimate and use the statistical properties of z_{t+1} from the residuals from the regression of equation (16) in the analysis. With autocorrelated residuals, however, estimated z values will not be independent and identically distributed (i.i.d.) as assumed in the Reed (1979) model. If the stochastic variable is not i.i.d., it is not possible to find an analytic solution to the optimisation problem. In this analysis we will therefore treat the z values as i.i.d. The fact that the z values are correlated means, nonetheless, that knowing the value of z in one period enables one to make better predictions about future z values. The assumption that the

[6] The lognormal distribution ensures that all z values are non-negative.

stochastic variable is i.i.d. thus makes it more difficult for a social planner to optimise expected net revenues from the fishery than it would be in the case when the z values are correlated. The net benefit from the fishery could therefore be higher under optimal management than what we find in the subsequent analysis by making this assumption about z_{t+1}.

Vessel Dynamics, Production Functions, Costs, and Prices

Bjørndal and Conrad (1987b) analyse capital dynamics in the North Sea herring fishery. They estimate several fleet-adjustment equations but unfortunately not equation (15). Data presented in Bjørndal and Conrad (1987, 1987b) are therefore used to estimate the adjustment parameter, n in equation (15). This gives us a point estimate of $n = 10^{-4}$.[7] Unless otherwise stated, this estimate will be used in the analysis.

Bjørndal and Conrad (1987) 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.[8] These are the Spence production function with $q = 0.0011$, and the Cobb-Douglas production function with $a = 0.06157$, $b = 1.356$, and $g = 0.562$.

Following Nøstbakken and Bjørndal (2003), cost data for Norwegian purse seine vessels with cargo capacity $8{,}000$ hectolitres and above is used in the analysis. Fixed costs are disregarded, since the vessels in question participate in several seasonal fisheries in addition to the North Sea herring fishery. This is appropriate, as the North Sea herring fishery is relatively minor compared to other fisheries and does not require any special

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

[8] 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.

equipment. The variable cost will not include costs associated with the crew, because crew remuneration represents a constant share of the vessel's revenue. The income will, therefore, be adjusted by a factor that represents the boat owner's share. The price used in the analysis is average price paid to the boat owners for North Sea herring, adjusted by a factor of 0.65, which represents the boat owner's share of income. See Nøstbakken and Bjørndal (2003) 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.

3. The North Sea Herring Fishery

In this part, the North Sea herring fishery is analysed by using the two production functions. In both cases, the open-access fishery and the optimally regulated fishery are considered. Stochastic simulations are used in the analysis. All simulations were programmed and run in MATLAB.

3.1 Model 1: The Spence Production Function

In the following section, the Spence harvesting relationship is used to analyse the optimally regulated and the open-access fishery.

The Optimally Regulated Fishery

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. 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 $\sigma_z^2 = 0.05$ and $\sigma_z^2 = 0.20$. As price increases, the difference between the curves grows, but not very much. For price $p = 5$ NOK/kg, the difference in optimal escapement level is about $136,000$ tonnes. As

$p \to \infty$, the optimal escapement level approaches 2.524 million tonnes ($\sigma_z^2 = 0.05$). 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.

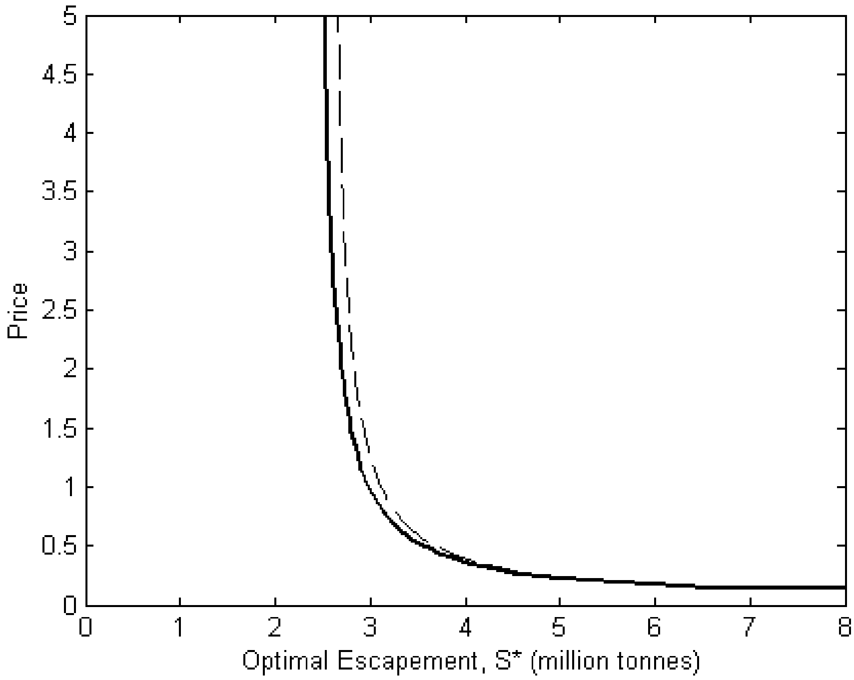

Figure 1. Optimal Escapement Level, Variance $\sigma_z^2 = 0.05$ (--) and $\sigma_z^2 = 0.20$ (c = 1,189,565 NOK, $\delta = 0.06$).

By simulating the optimal harvesting rules over a long time period, we can find the statistical distributions of X_t, Y_t, etc. Figure 2 shows the average long-term levels of biomass and harvest for different prices with confidence intervals.[9] For harvest, only the upper confidence limit can be seen for the reason that the lower level is below zero. The

[9] A 66-percent confidence interval is shown in the figure, i.e., the mean plus or minus one standard deviation. 66-percent confidence intervals are used in the remainder of the paper unless otherwise stated.

figure shows that the confidence level seems to be fairly constant for different prices. It also shows that the relative variation in stock level is less than the variation in annual harvest. For prices above $p = 2$ NOK/kg, biomass is some 3 million tonnes and the corresponding harvest is close to $700,000$ tonnes. The shape of the harvest curve in Figure 2b is very similar to Nøstbakken and Bjørndal's (2003) discounted equilibrium supply curve for the North Sea herring fishery.

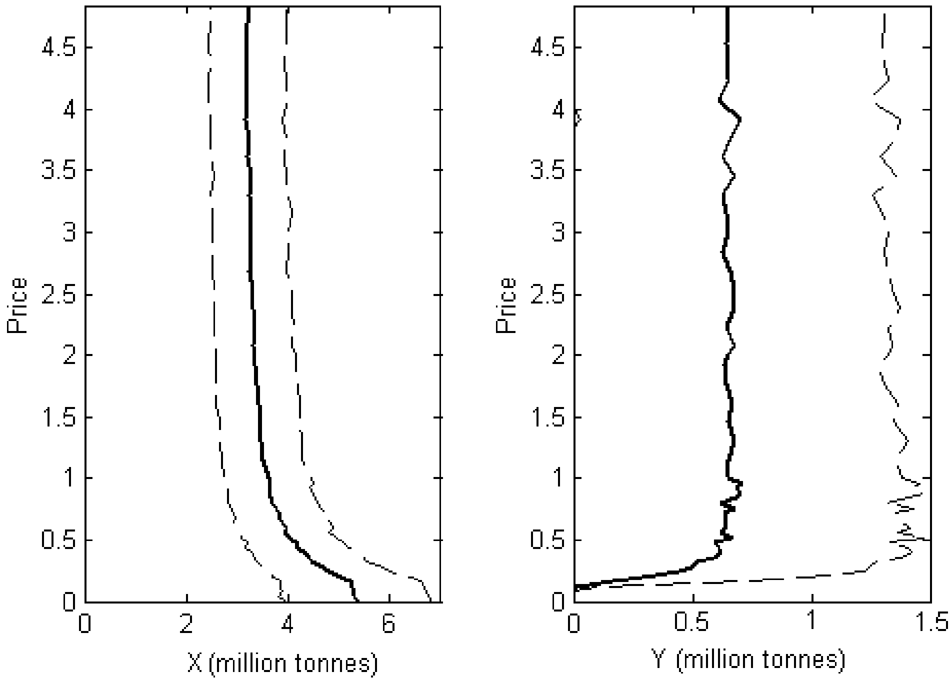

Figure 2. Stock and Harvest with Confidence Intervals for Different Prices at Time t=100.

The Open-Access Fishery

Stochastic simulations of the open-access fishery are run for different prices. The carrying capacity of the environment, L, was used as the initial value for biomass, and the initial number of vessels was set to $K = 120$. As price approaches infinity, so does effort, and escapement $S \to 0$. However, the simulation results show that the stock can be severely depleted even at more realistic prices than $p \to \infty$. Figure 3 and Figure 4 show some of the results from $N = 1,000$ simulations of the fishery over $T = 200$ years.

Figure 3 gives stock and catch dynamics with confidence intervals for price $p = 2$. The long-term equilibrium stock level for this price is about $710,000$ tonnes with a corresponding annual catch of about $215,000$ tonnes. The figure shows that there is overshooting and subsequently damped oscillation toward the equilibrium levels of biomass and harvest.

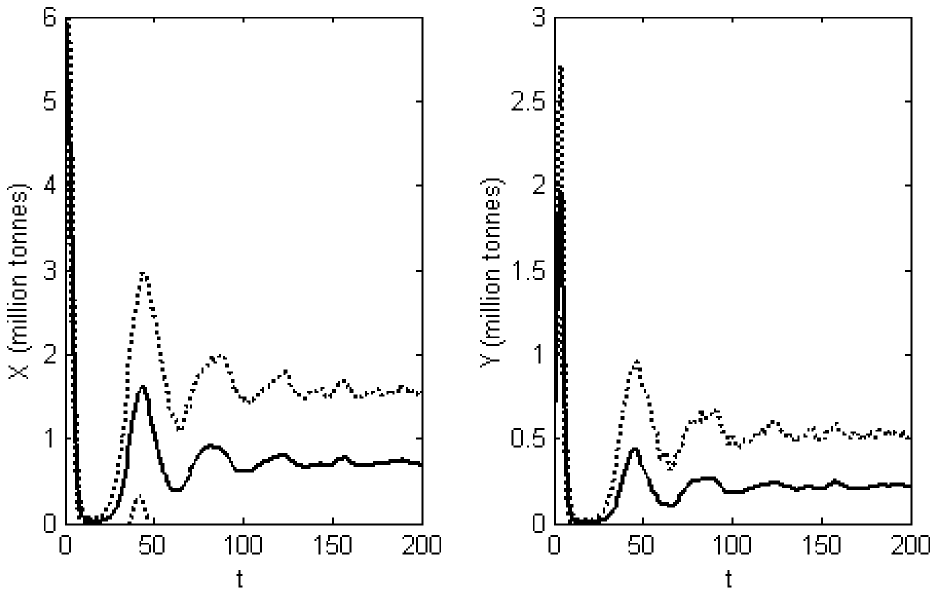

Figure 3. Stock and Catch Dynamics with Confidence Intervals (c = 1,189,565 NOK, p=2 NOK/kg).

The number of vessels in the fishery also oscillates toward the long-term equilibrium level, as can be seen in Figure 4a. If a different adjustment parameter had been used, the degree of overshoot would have been different (see Figure 4b, where $n = 5 \cdot 10^{-5}$). With $n = 10^{-4}$, as in Figure 4a, both biomass and catch are close to zero between $t = 10$ and $t = 25$. In some of these periods, the biomass is under $20,000$ tonnes, and the annual harvest is as low as about $5,000$ tonnes. As mentioned earlier, the stock cannot be driven to zero unless $K \to \infty$ when the Spence production function is used. This explains why the stock after a long time period starts growing again and subsequently stabilises at the open-access equilibrium level.

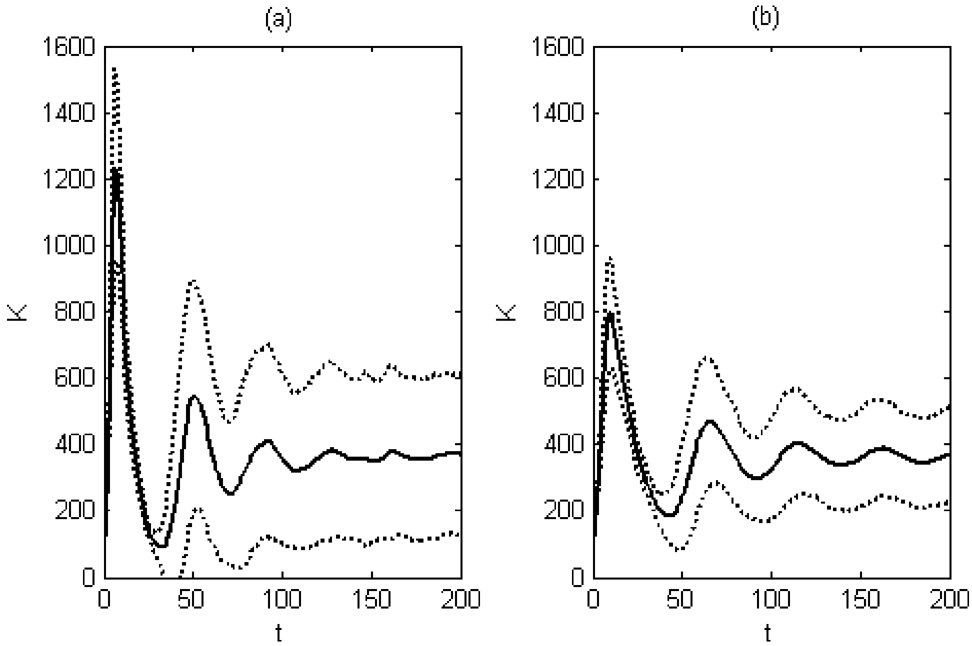

Figure 4. Vessel Dynamics with Confidence Interval, Adjustment Parameter (a) $n = 10^{-4}$ and (b) $n = 5 \cdot 10^{-5}$ (c = 1,189,565 NOK, p = 2 NOK/kg).

The dramatic initial increase in K that can be seen in Figure 4a can also be explained by the initial values of biomass and number of vessels that were chosen. The small number of vessels that harvests from the relatively large stock of size L in the first period earns very high net revenues. Since it was assumed that vessel dynamics follows the sign and size of the normalised net revenue per vessel, the subsequent increase in the number of vessels is very high.

Figure 5 shows the distributions of X and Y at time $T = 200$ for different prices. For the stock, X, zero is within one standard deviation from the mean if the price is higher than 1.7 NOK/kg. Although X never reaches zero (unless $p \to \infty$), it gets so close that the stock virtually has gone extinct even for the prices shown in this figure. The harvest curve, Y, can be regarded as a stochastic equivalent to the backward-bending open-access supply curve described by Copes (1970) and estimated for the North Sea herring fishery by Nøstbakken and Bjørndal (2003).

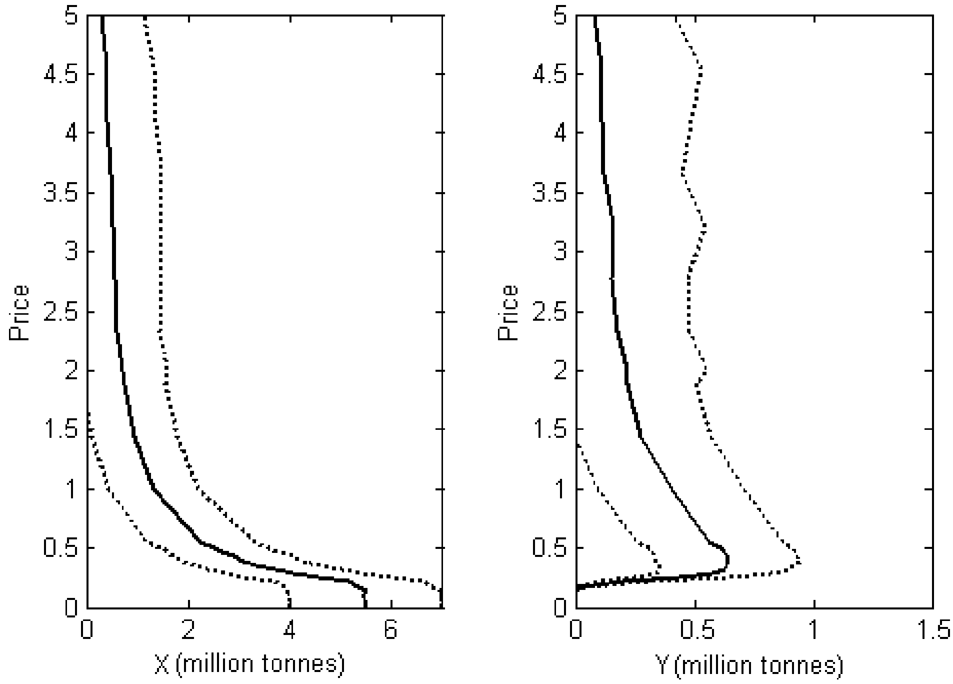

Figure 5. Stock and Harvest at Time t=200 with Confidence Intervals (c = 1,189,565 NOK).

3.2 Model 2: Cobb-Douglas Production Function

The optimally regulated and the open-access fishery will now be analysed for the Cobb-Douglas production function.

The Optimal Linear Feedback Policy

Optimal linear feedback policies (equation (14)) 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 α and β in the linear feedback equation (14) 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 β stays very close to 1, although it decreases with price. Optimal α increases with price, but the relative change in α is small. For price $p = 2$, the optimal linear feedback policy is approximately $Y_t = \text{-2,850,000+0.99X}_t$. For positive values of X_t, harvest will never equal total stock and extinction of the stock is therefore never optimal when $p = 2$. Recall from section 2.2 the "common sense" condition for harvest $0 \le Y_t \le X_t$. We know the above feedback policy ensures that $Y_t < X_t$. From the condition $Y_t \ge 0$ we thus get the following optimal (linear) feedback policy for the North Sea herring fishery ($p = 2$):

$$Y_t = \begin{cases} 0 & \text{if} \quad X_t < 2,880,000 \\ (\text{-2,850,000+0.99X}_t) & \text{otherwise} \end{cases} \tag{17}$$

Figure 6 shows the simulation results for price $p = 2$ based on the feedback policy given by equation (17). After a transition period, the mean values of biomass and harvest 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 (cf. section 2.3). If we, however, look at the simulations separately, we see 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. This is illustrated in Figure 7, were stock and catch dynamics from one of the simulations are shown.

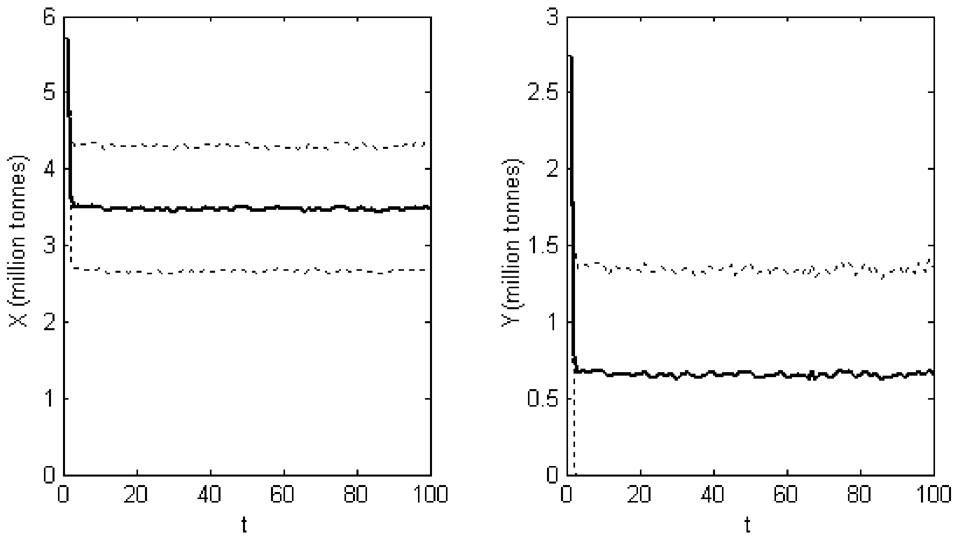

Figure 6. Stock and Catch Dynamics with Confidence Intervals (c = 1,189,565 NOK, p = 2 NOK/kg, $\delta = 0.06$).

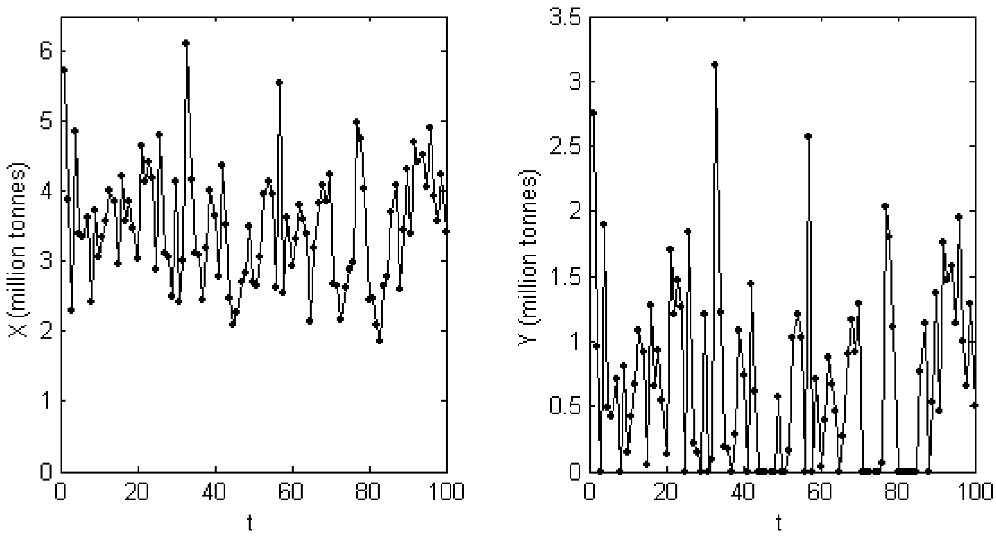

Figure 7. Stock and Catch Dynamics from One Simulation (c = 1,189,565 NOK, p = 2 NOK/kg, $\delta = 0.06$).

The Open-Access Fishery

Stochastic simulations of the open-access fishery result in depletion of the fish stock in all the $N = 1,000$ simulations (before time $T = 100$), given that price is above a minimum level that makes fishing viable in the first place. Initial biomass and number of vessels was set to L and 120, respectively. Bjørndal and Conrad (1987) studied the dynamics of the North Sea herring fishery using a deterministic model and the same Cobb-Douglas production function as used here. They concluded that the likelihood of overshooting and possible extinction under open access is greater with discrete adjustments. In the model employed in this paper, we have a stochastic component in the recruitment function. This increases the likelihood of overshooting further compared to the deterministic case.

Time of total extinction of the fish stock is shown in Figure 8a for different prices. If price is above 1.1 NOK/kg, it is very likely that the stock will go extinct within 30 years under an open-access regime. The variance in time of extinction is very small for prices above 1.2 NOK/kg. In these cases, the simulation results imply that the stock will go extinct after five to ten years. Figure 8b shows biomass at time $T = 100$ for different prices. This figure also shows that if price is 1.1 NOK/kg or higher it is highly unlikely that the stock will survive under open access.

Time of extinction is influenced by the initial values for biomass and number of vessels that are used in the simulations. As in the open-access case for Model 1, there is a very large increase in number of vessels from the first to the second time period because of high net revenues in the first period resulting from the initial values of K and X that were used. However, the choice of initial values does not affect the conclusion that the stock eventually will go extinct under an open-access regime as long as price is above 1 NOK/kg.

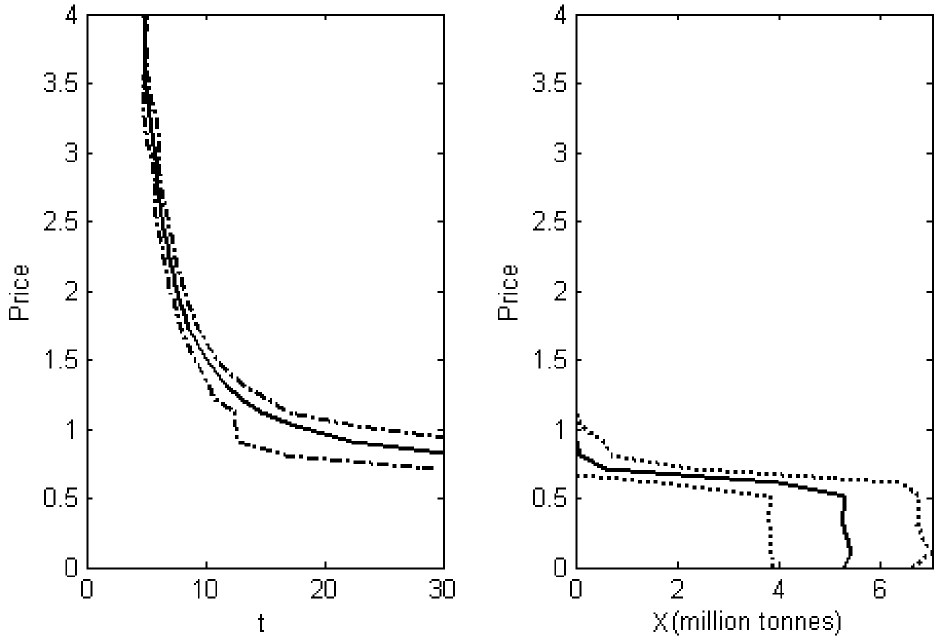

Figure 8. Open Access: Time of Extinction and Biomass at Time t=100 with Confidence Intervals (c = 1,189,565).

3.3 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 the $N = 1,000$ simulations show that for Model 2 (Cobb-Douglas production function) 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. Recall that for this model, price has to approach infinity for the stock to go extinct. For Model 1, 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 9 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 9, Model 1 and Model 2 follow almost the same path with an increasing number of vessels and decreasing stock. The approximate change in number of vessels is from 400 to 550 in Model 1 and from 440 to 600 in Model 2. The corresponding change in biomass is from $1,650$ thousand tonnes to 640 and 160, respectively. While this change only takes four years in Model 2, the same process takes about six years in Model 1.

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.[10] We therefore have no real observations to compare the simulation results to.

[10] See Nøstbakken and Bjørndal (2003) on regulations of the North Sea herring fishery 1981-2001.

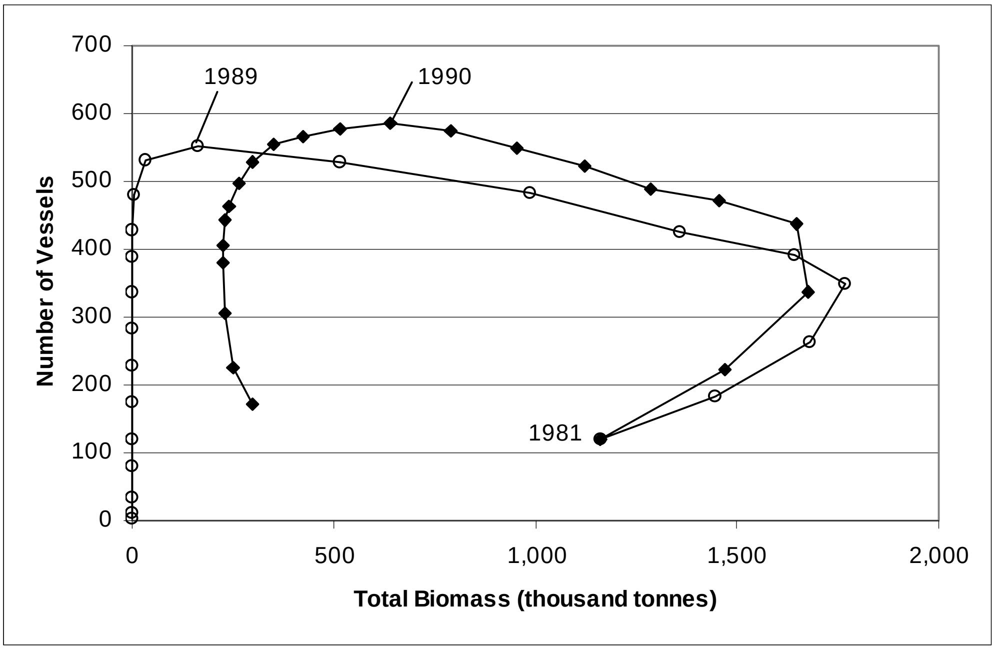

Figure 9. Open-Access Dynamics, Model 1 (♦) (Spence) and Model 2 (Cobb-Douglas), 1981-2002.

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 (1987). 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 harvesting 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 10. The actual harvest and stock, on the other hand, deviate from these optimal harvesting policies.

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 as low as 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 10.

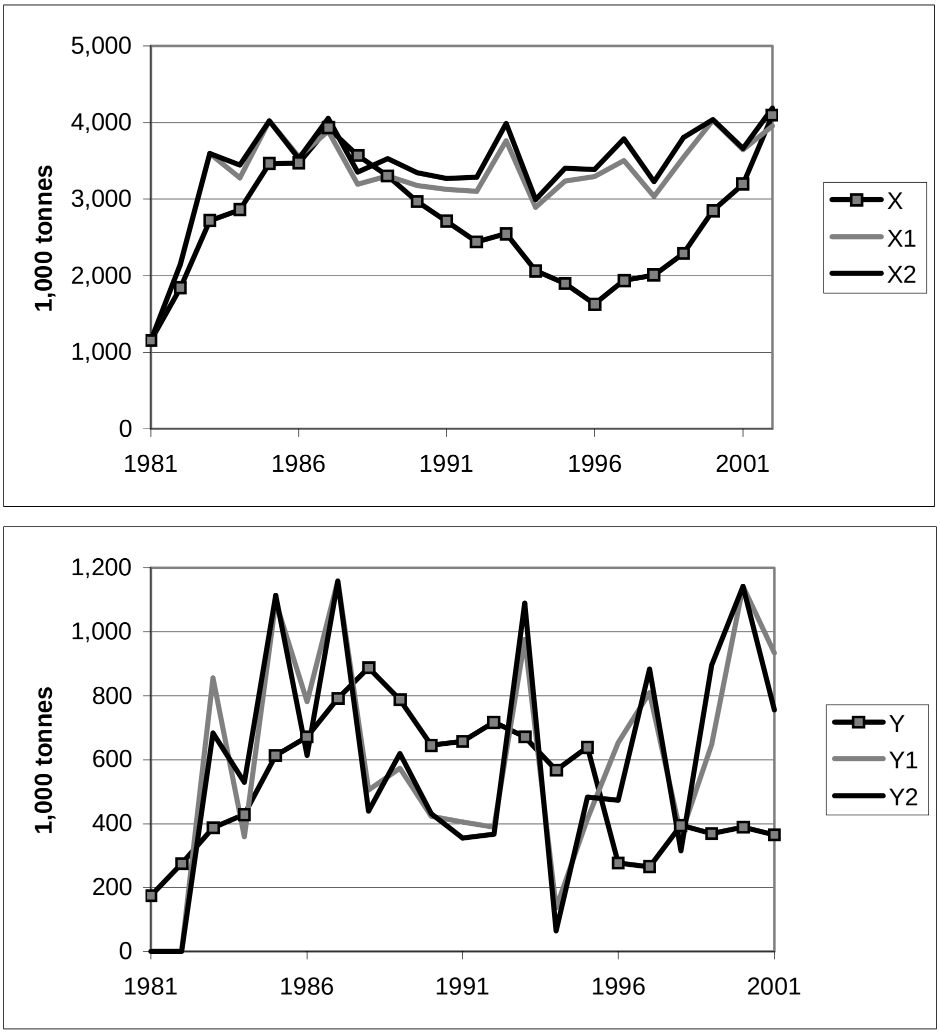

Figure 10. Optimal Policies, Models 1 (Spence) and 2 (Cobb-Douglas) Versus Actual Policy; Stock Levels 1981-2002 (top) and Annual Catches 1981-2001 (bottom), $\delta = 0.06$.

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 is about 4.32

million tonnes according to ICES. The stock has thus been allowed to grow to a level above the level that maximises net revenues from the fishery.

Figure 11 shows sum of present value of net revenues from 1981 onwards for the two optimal harvesting policies and actual harvest.[11] The two optimal harvesting policies derived from the bioeconomic model give almost the same net revenues, although the optimal escapement policy for the Spence production function gives marginally higher discounted net 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.

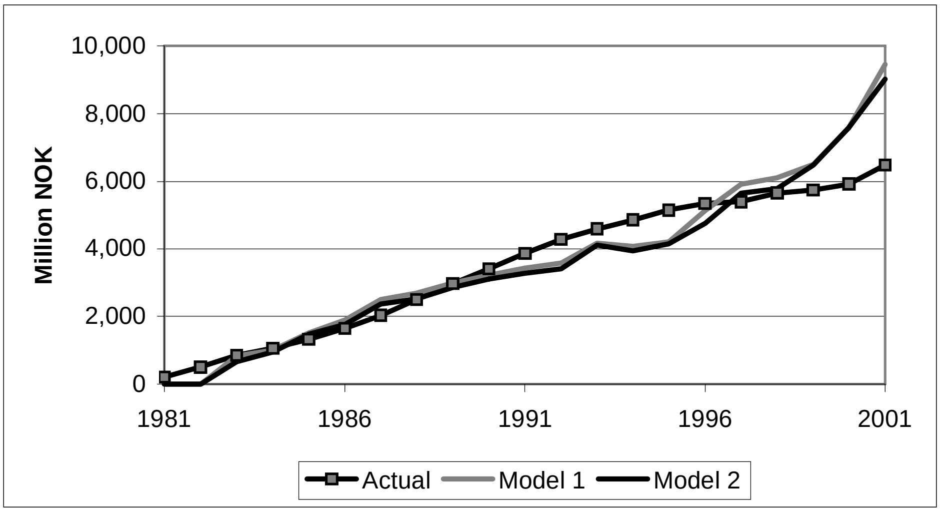

Figure 11. Sum of Present Value of Revenues from 1981 Onwards.

The actual policy has the highest net 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

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

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 10, the actual stock level (X) equals the optimal stock levels ($X1$ and $X2$) 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 linear feedback policy *can* be the best of all possible feedback policies. There might, however, be non-linear feedback policies that outperform the optimal linear feedback policy. Nevertheless, the fact that the linear feedback policy gives almost the same results as the optimal escapement policy (Model 1) indicates that a linear feedback probably is close to the optimal policy.

In this section we have seen that the difference 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.

4. Summery and Conclusions

In this paper, harvesting or supply of North Sea herring has been analysed. A stochastic model has been 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 environmental 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. The long-term supply in an open-access fishery was seen to be positive for the Spence production function given that price is high enough for fishing to be viable. We found that the corresponding result for the Cobb-Douglas production function was total extinction of the fish stock and consequently no harvesting. Herring prices are and have been more than high enough for the stock to go extinct (Model 2: Cobb-Douglas) if the fishery is left unregulated. Although the results in terms of long-term supply are very different between the two models, predicted supply in periods when biomass is not close to extinction was found to be quite similar between the models.

In an optimally regulated fishery, the Spence production function leads to a constant-escapement rule as proved by Reed (1979). 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 found 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 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 (2003) 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 (2003) results for the deterministic case.

This paper represents a continuation of the work in Nøstbakken and Bjørndal (2003). The current analysis can be extended in several ways. One possibility would be to introduce measurement error in the stock estimates (cf. Clark and Kirkwood 1986). This would also allow for an analysis of optimal management instruments (cf. Weitzman 2002), 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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