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Market based supply of

North Sea Herring and Icelandic Cod

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Abstract

A continuous-time bioeconomic model is developed and used to derive open-access and optimal management supply curves. Long-run equilibrium supply curves are estimated based on data for two fisheries: North Sea herring and Icelandic cod. The two species in question have very different biological characteristics. While the North Sea herring is a pelagic species found in schools in the sea, the Icelandic cod is a demersal species. Consequently, the methods used to harvest the two stocks are quite different. Based on the particularities of the fisheries in question, different production/cost functions have been used in the bioeconomic models. Different regulatory regimes in the fishery over the past two decades, both actual and theoretical, are evaluated with respect to effects on supply and stock levels. The results indicate that different regulations, as well as the biological characteristics of the species, can have a substantial impact on the supply of fish.

0. INTRODUCTION

While demand functions and market structure receive substantial attention in the fisheries economic literature, very little attention is given to the supply side in fisheries. The backward-bending open-access supply curve was derived in the seminal paper by Copes (1970). With the advent of optimal control theory, Clark (1990) derived the equilibrium supply curve for an optimally managed fishery. However, the literature contains few, if any, empirical studies of fisheries supply curves. Bjørndal (1987) estimated a harvest supply function, but the purpose of his study was to use duality to retrieve the characteristics of the underlying production technology, and the supply function *per se* was not derived. As one of the few empirical applications in the literature, Nøstbakken and Bjørndal (2003) estimate supply functions for North Sea herring, both under open access and optimal management.

The purpose of this paper is to derive and estimate supply functions. A bioeconomic model will be developed and used to derive supply curves for the open-access regime and the optimally managed fishery.   These supply curves will then be empirically estimated based on data for two fisheries. One is a fishery on a schooling stock, namely North Sea herring, and the other is a fishery on a demersal stock, Icelandic cod. These two fisheries differ widely both with regard to biological characteristics and harvest technology.

As noted, supply functions for fish have received little attention in the literature. This is strange, for a number of reasons. In fisheries, as in other sectors of the economy, observed price and quantity figures will be a result of the interaction between supply and demand, as well as government regulations. In such a context, it is important to identify and attempt to quantify the impact of the supply side.

A possible reason for this neglect of the supply side is that, in most bioeconomic models, price is assumed to be fixed. Often, this assumption is made to simplify an analysis of optimal resource management. In our analysis, we want to analyse and quantify how the supply of fish varies with price under different assumptions. Knowledge about the supply function is important with respect to analysis of the fishery under optimal management, open access, and other regulatory regimes. From the perspective of market analysis, knowledge about the supply function is essential. Furthermore, it may help explain the past development of different fisheries.

In the next section, a bioeconomic model is developed, and equilibrium supply curves for the open access and the optimally managed fisheries are derived. The empirical analysis is presented in section two, where supply curves are estimated for North Sea herring and Icelandic cod under different sets of assumptions. The paper is summarised in the final section.

1. THE BIOECONOMIC MODEL

Changes in the biomass of a fish stock over time come from recruitment, natural growth, natural mortality, and harvesting. This can be explained by the following equation:

$$\dot{X} = F(X) - Y, \tag{1}$$

where $X = X(t)$ is the total biomass, $F(X)$ is the instantaneous natural growth of the biomass, and $Y = Y(t)$ is the catch rate. The natural growth of the biomass is explained by the logistic growth function:

$$F(X) = rX\left(1 - \frac{X}{K}\right), \tag{2}$$

where r is the intrinsic growth rate, and K is the carrying capacity of the environment.

Net revenues or industry profits from a fishery can be written as a function of current stock and harvest rate:

$$\pi(X,Y) = pY - C(X,Y), \tag{3}$$

where p is unit price of harvest. The industry profit equals the resource rent from the fish stock.

With the basic model in place, we turn to the derivation of equilibrium supply curves for the open access and optimal management fisheries.

1.1 The Open-Access Fishery

The equilibrium in an open-access fishery is known as the bionomic equilibrium (Gordon 1954). The conditions for bionomic equilibrium are: i) harvest equal to natural growth so that

the stock is kept in steady state; i.e., equation (1) is equal to zero, and ii) net revenues (equation 3) equal to zero. We will return to these in the empirical applications below.

1.2   The Optimally Managed Fishery

We assume that a sole owner, whose objective is to maximise the present value of net revenues from the fishery, manages the fish stock. The maximisation problem can be written as:

$$\max_{\{Y\}} \int_0^\infty e^{-\delta t} \pi(X, Y) dt, \tag{4}$$

where δ is the social rate of discount, subject to (1) and $X(0)$ given. This is an optimal control problem, where X is the state variable, and Y is the control variable. By applying the maximum principle, we can derive the steady-state version of the well-known fundamental equation of renewable resources:

$$F'(X) + \frac{\partial \pi / \partial X}{\partial \pi / \partial Y} = \delta. \tag{5}$$

In addition we know that $F(X) = Y$ in steady state. Because we assume that revenues are linear in harvest (constant price), equation (5) can be rewritten as:

$$F'(X) - \frac{\partial C / \partial X}{p - \partial C / \partial Y} = \delta. \tag{6}$$

Depending on the choice of cost function, it can be difficult, or even impossible, to solve equation (6) for the steady-state stock or harvest levels. It is however possible to solve for price:

$$p = \frac{\delta C}{\delta Y} + \frac{\partial C / \partial X}{F'(X) - \delta}. \tag{7}$$

In addition, the following condition must hold in equilibrium:

$$Y = F(X) = rX\left(1 - \frac{X}{K}\right) \tag{8}$$

Using equations (7) and (8), we can find optimal equilibrium combinations of price and yield. Clark (1990) refers to the resulting supply curve as the discounted supply curve.

2. EMPIRICAL ANALYSIS

In this section we will look at two applications; North Sea herring and Icelandic cod.

2.1 **The North Sea Herring Fishery**

The North Sea autumn spawning herring (*Clupea harengus*) is a pelagic stock that lives on plankton. The stock consists of three spawning stocks with different spawning grounds: the northern, central, and southern North Sea.

Herring of the central and northern populations spawn in August and September in the western North Sea. After spawning, the herring migrate eastwards to spend the winter in the Norwegian Trench. In spring, the fish migrate north along the Norwegian Trench and then west towards Shetland. In May-June, the feeding starts in the northern part of the North Sea. The southern population spawn in December and January in the eastern English Channel. After spending the winter in the southern part of the North Sea, the herring migrate directly to the feeding grounds in the central and northern North Sea. It is normal to treat the three stocks as one, because they mix on the feeding grounds, rendering it impossible to distinguish between catches from the different stocks. The herring fishery takes place primarily in the central and northern North Sea during the months May to September.

The North Sea herring 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. However, in the mid-1990s the stock once again was outside safe biological limits, and in 1996 the total quota was reduced to save the stock from collapse. To rebuild the stock, the quotas have been relatively small since 1996 (Nøstbakken and Bjørndal, 2003). Recent stock estimates show that it has been rebuilt above the level that guarantees good recruitment (ICES 2002a).

Figure 1 shows the historical development in spawning stock and landings of North Sea herring. The figure shows how the spawning stock collapsed in the late 1960s, followed by over a decade of very low stock level and harvests. Even though the spawning stock was only some 100 thousand tonnes, the annual harvested quantities of fish during this period were much higher than the spawning stock. The figure also shows the aforementioned stock decline

in the 1990s. Spawning stock in 2002 is seen to be at the same level as in the early 1960s before the severe depletion of the stock started.
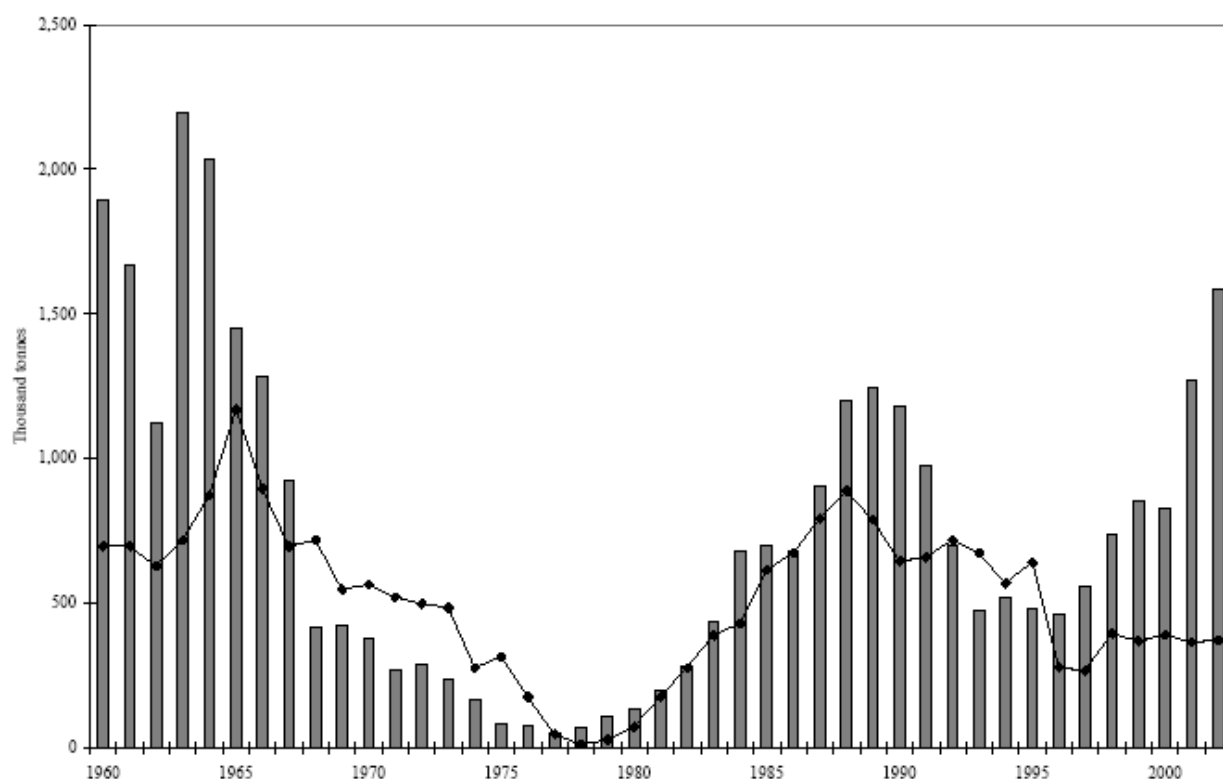

Figure 1. North Sea Herring: Spawning Stock Biomass (bars) and Harvest

Source: ICES.

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). Management decisions are, therefore, agreed upon by Norway and the EU. In 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.[1] 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.[2] In addition, the EU gets the entire bycatch quota.

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[1] Source: Anon. 2001.
[2] See Bjørndal and Lindroos (2004) on the sharing of the resource between Norway and the EU.

Table 1. Herring Price (NOK/tonne), Harvest and Stock in Tonnes, 1998-2001[a].

	1998	1999	2000	2001
Price (NOK per tonne)	1,547	1,210	1,318	2,465
Harvest (tonnes)	380,200	372,300	372,400	364,000
Stock size (tonnes)	2,189,700	2,464,400	3,118,900	3,590,600

[a] Sources: ICES 2002a and the Norwegian Directorate of Fisheries.

Annual average herring price, harvest and stock size are given in Table 2 for the years 1998-2001. It is remarkable that while harvest remained fairly constant over this period, price fluctuated quite substantially: first a 20% reduction from 1998-1999, followed by a doubling from 1999-2001. As the catch was nearly constant, an explanation for this development must be sought elsewhere in the interactions between supply and demand.

Bjørndal and Conrad (1987) estimated a Cobb-Douglas production function, $Y = aE^b X^g$, for the North Sea herring fishery According to these authors, the number of participating vessels may be an appropriate measure of effort, an assumption that will also be made in this article.

The schooling behaviour of the herring has permitted the development of very effective means of harvesting. With modern fish finding equipment, harvesting can be viable even at very low stock levels. For this reason, we will expect $0 \le g < 1$ for herring. The Cobb-Douglas production function will describe a "pure" schooling fishery, where catch is independent of stock, when $g = 0$ (Bjørndal 1988).

Variable cost will not include costs associated with the crew, because crew remuneration represents a constant share of the vessel's revenue. We will, therefore, adjust the income by a factor that represents the boat owner's share. This leaves us with the boat owner's share of both prices and variable costs.

The estimating equation for the growth function in equation (2) is: [3]

$$(X_{t+1} - X_t) + Y_t = rX_t - \frac{r}{K} X_t^2 = \beta_1 X_t + \beta_2 X_t^2 + u_t. \tag{9}$$

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[3] Bjørndal (1988) developed and estimated a delay-difference model of population dynamics. Bjørndal and Contrad (1987) found that the Schaefer model was a good approximation of this more complicated model. As will be seen, the statistical fit of the model is also good.

Nøstbakken and Bjørndal (2003) estimate growth functions under different alternatives. According to their "preferred" estimates, the intrinsic growth rate of the biomass, r, is about 0.53 and the carrying capacity of the environment, K, is about 5,270,000 tonnes. The estimate of the intrinsic growth rate is very close to the corresponding estimate reported by Bjørndal (1988) of 0.52, which was based on estimating a delay-difference model of population dynamics. Arnason, Magnusson, and Agnarsson (2000) report an estimate of the intrinsic growth rate for Norwegian spring spawning herring of 0.47. Thus, the estimate of the intrinsic growth rate presented appears to be very robust.

Bjørndal and Conrad (1987) used Norwegian purse seine data for the period 1963 – 1977 to estimate the Cobb-Douglas production function, for the herring fishery and obtained:

$a = 0.06157$

$b = 1.3556$

$g = 0.5621.$

The parameter estimates show that the Schaefer production function is inappropriate for the North Sea herring fishery. The parameter g reveals, as expected, the output elasticity of stock size to be between zero and one. Thus, harvest will decrease with decreasing stock size, but is not very sensitive to changes. The parameter b indicates an output elasticity of effort larger than one. This means that increased effort is met with increasing harvest. This may be the result of economies of scale in the search for schools of herring.

Bjørndal and Conrad (1987) also estimated the production function for a pure schooling fishery as a special case. With $g = 0$ imposed, they obtained the following parameter estimates for the Cobb-Douglas production function by OLS regression:

$a_s = 93.769$

$b_s = 1.4099.$

Even if the Cobb Douglas functional form $Y_t = a K_t^b X_t^g$ resulted in the most plausible values for the bionomic equilibrium and open-access dynamics (Bjørndal and Conrad 1987), the pure schooling fishery is an interesting case. As pointed out by Bjørndal (1988) the optimal stock levels under this assumption are always less than or equal to optimal stock levels with density-dependent costs.

Several countries harvest the North Sea herring stock. By estimating the production function using data from the Norwegian purse seine fleet, fishing effort, *K*, may be interpreted as an estimate of "purse seine equivalents" fishing herring in the entire North Sea (Bjørndal and Conrad 1987). The parameters of the production function estimated by Bjørndal and Conrad (1987) will be used in the current analysis. Their 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, represented by the constant term, *a*, may be somewhat underestimated due to technological development.

Price and cost data are also from the study by Nøstbakken and Bjørndal (2003). All prices and costs are in real 2001 NOK. Cost data for the Norwegian purse seine fleet will be used, and data for purse seine vessels is used in the analysis. Fixed costs are disregarded, because 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 equipment.

The price used is the 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.

Open-access equilibrium

From equation (3) and the production function we obtain expressions for the open-access stock and effort levels:

$$X_\infty = \left(\frac{c}{paE^{(b-1)}} \right)^{\frac{1}{g}} \tag{10}$$

$$E_\infty = \frac{pY}{c} \tag{11}$$

Hence, we can express the sustainable yield, Y_∞, in terms of price, *p*, and effort, *E*:

$$Y_\infty = r \cdot \left(\frac{c}{paE_\infty^{(b-1)}} \right)^{\frac{1}{g}} \cdot \left[1 - \frac{1}{K} \cdot \left(\frac{c}{paE_\infty^{(b-1)}} \right)^{\frac{1}{g}} \right] \tag{12}$$

Equilibrium supply is given by equations (11) and (12). While it is not possible to solve for explicit expressions for Y_∞ and E_∞ unless $b = g = 1$, it is possible to solve for Y_∞ and E_∞ numerically. If $b = g = 1$, steady-state open-access stock is given by $X_\infty = c/ap$, given that the stock size constraint $0 \leq X \leq K$ holds (follows from equation 1). Long-run supply and

effort are hence given as $Y_\infty = r\left(c/ap\right)\left[1 - \dfrac{\left(c/ap\right)}{K}\right]$ and $K_\infty = \left(p/c\right)Y_\infty = \left(r/a\right)\left[1 - \dfrac{\left(c/ap\right)}{K}\right]$ in

the case $b = g = 1$.

A pure schooling fishery is a special case of the Cobb-Douglas harvest function with a stock – output elasticity of zero. In this case, the cost of harvesting is independent of the stock level. Thus, depending on the price-cost relationship, the fishermen will either increase the fishing effort until the stock is depleted, or they will not harvest at all. Either way, the equilibrium supply would be zero. With $b = 1$ and $g = 0$, the stock would be depleted if $p > \dfrac{c}{a}$ (Bjørndal 1988).

Optimal management equilibrium

In the general case, where the production function is $Y = aE^b X^g$, the corresponding cost function can be written as follows:

$$C(X,Y) = c\left(\frac{Y}{aX^g}\right)^{1/b},$$ (13)

where c is the constant cost per unit of effort in the fishery. Taking partial derivatives and inserting into equation (7) gives us an expression for the discounted supply curve:

$$p = \frac{c}{bY}\left(\frac{Y}{aX^g}\right)^{\frac{1}{b}} - \frac{\dfrac{cg}{bX}\left(\dfrac{Y}{aX^g}\right)^{1/b}}{r - 2rX/K - \delta}$$ (14)

We will also find the equilibrium solution for a pure schooling fishery ($g = 0$ in the Cobb-Douglas function). The optimum is in this case given by:

$$F'(X) = \delta .(15)$$

As there is no (long-run) harvesting if profit is negative, equilibrium supply in a pure schooling fishery is given by:

$$Y^* = \begin{cases} \dfrac{K}{4r}\left(r^2 - \delta^2\right) & \text{if } p > \dfrac{c}{Y^*}\left(\dfrac{Y^*}{a}\right)^{\frac{1}{b}} \\ 0 & \text{otherwise} \end{cases}. \tag{16}$$

From equation (16) we can see that in a pure schooling fishery, the supply is independent of price and costs, as long as the price-cost ratio is above a certain level.

Comparing open access to optimal management, the possibility exists that the long-run supply from an open-access fishery will be zero, which is the case if the stock is driven to extinction. Equilibrium supply will be higher under optimal management than under open access.

Equilibrium Supply Curves for North Sea Herring

Using the estimated parameters, we are now able to plot equilibrium supply curves. The open-access equilibrium supply curve for $c = 1,091,700$ is shown in Figure 2. $c = 1,091,700$ represents the cost per purse seine vessel in the North Sea herring fishery in 2000. The shape of the curve is backward bending (Copes, 1970) as a consequence of the biological overfishing that occurs when effort exceeds the level corresponding to maximum sustainable yield (Clark 1990).

The supply is zero if the adjusted price is 495 NOK/tonne or less. The reason is that fishing will not be viable at such low price levels. For prices above 495 NOK/tonne, the supply increases to the MSY, and subsequently decreases toward zero again. MSY = 698,275 tonnes is reached when the price is 544 NOK/tonne.
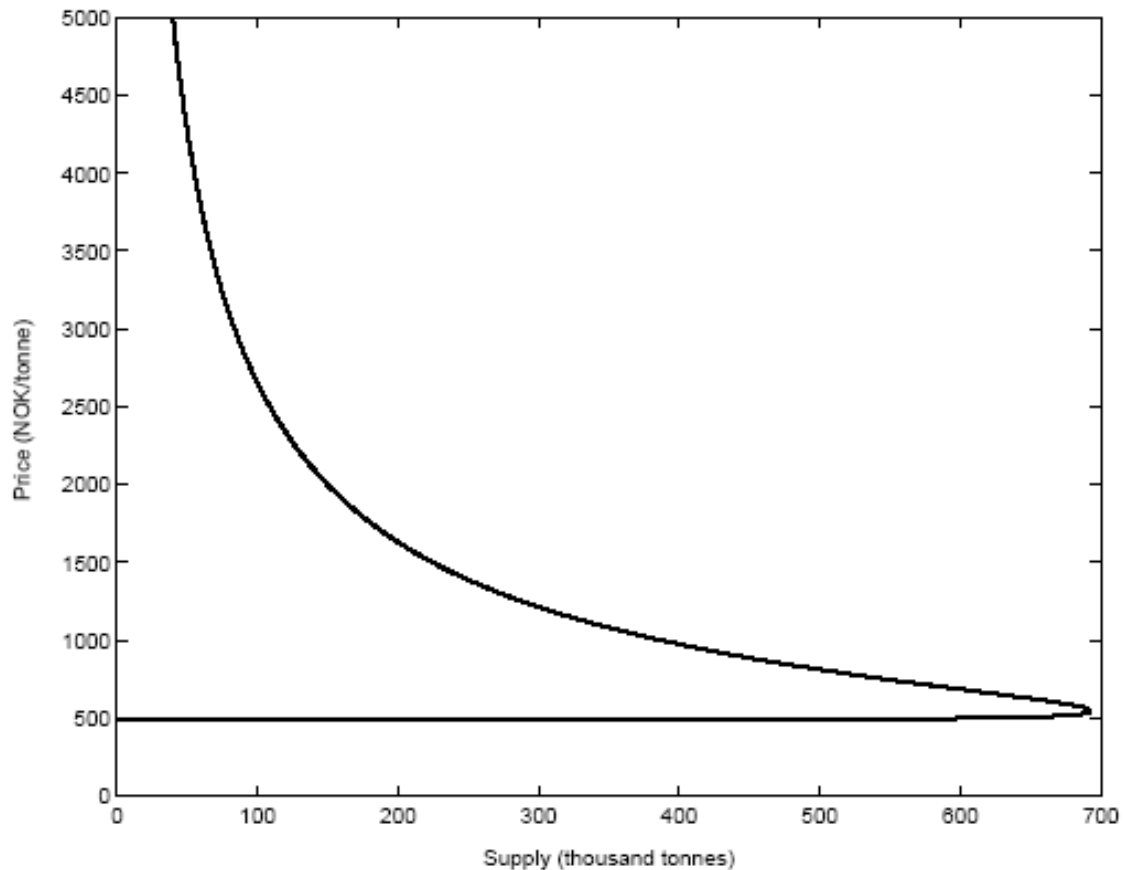
Figure 2. North Sea Herring: The Open-access Equilibrium Supply Curve

Figure 3 shows the equilibrium supply curve for the optimally managed fishery when c = 1,091,700 and alternative discount rates of 0 and 6%. For $\delta > 0$, the discounted supply curve is backward bending, but the degree of backward bending depends on the rate of discount employed. For a small δ, the degree of backward bending will be modest. For $\delta = 0$, the supply approaches MSY as price increases.

Similar to the case of open access, the discounted supply will be zero if the price is 495 NOK/tonne or less. If the discount rate is 6%, supply will increase with price until p_{msy} = 1,397 NOK/tonne is reached and the supply is MSY = 698,275 tonnes. Subsequently, the supply decreases towards a level of 689,325 tonnes.

Regardless of the discount rate, once the price is above a certain level (approximately $p > 2,000$) equilibrium supply is virtually constant. Thus, even large changes in the price will have only a minor impact on discounted supply.
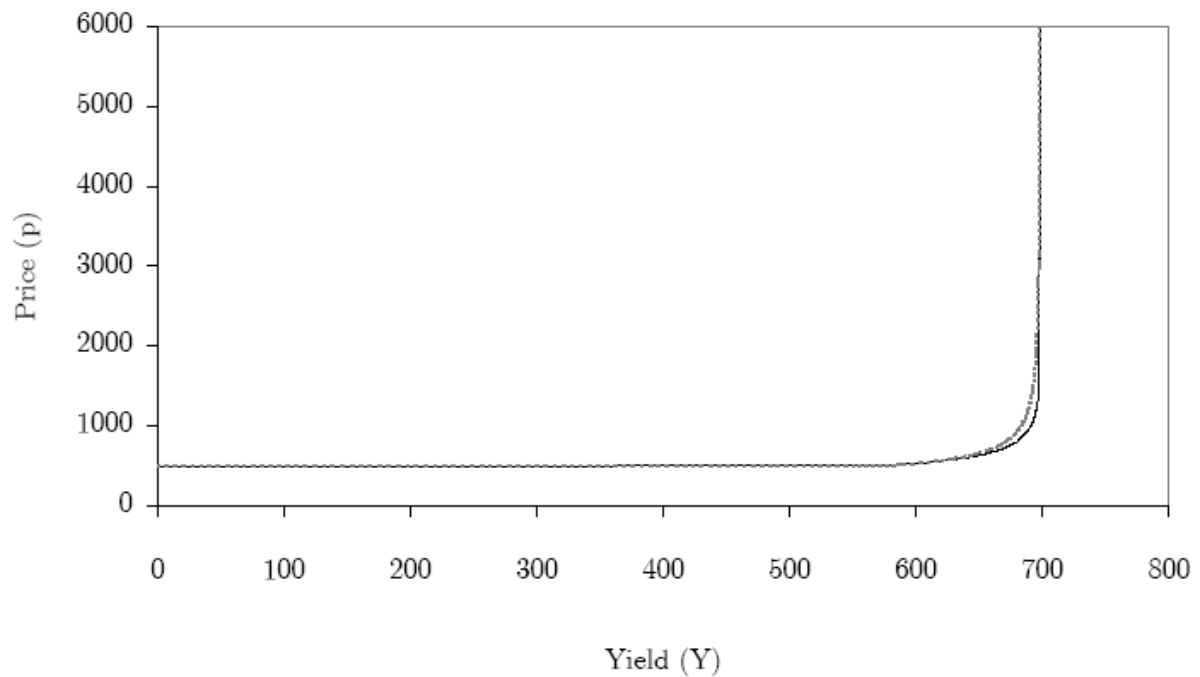
Figure 3. The Discounted Supply Curve, δ = 6% (thick line) and δ = 0.

Figure 4 shows equilibrium supply curves for the optimally managed pure schooling fishery. In this fishery, the equilibrium supply will be zero if the price is less than 875 NOK/tonne. For prices above 875 NOK/tonne, the equilibrium supply is positive and independent of price as long as $\delta \leq r$. If $\delta > r$, the stock will be driven to extinction and the equilibrium supply will be zero. The equilibrium supply is decreasing in the rate of discount. For prices above 875 NOK/tonne, the supply is MSY = 698,275 tonnes for $\delta = 0$ and 689,325 tonnes for $\delta = 6\%$. The optimally managed pure schooling fishery represents limits for the optimal stock level.
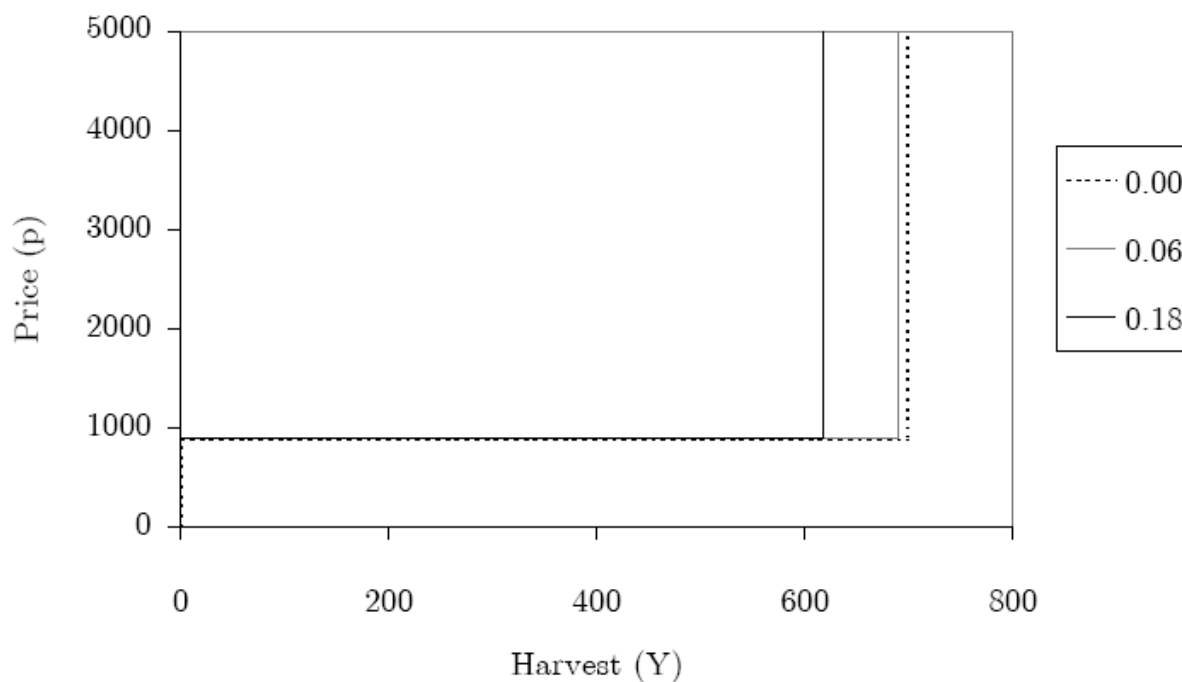
Figure 4. North Sea Herring: Equilibrium Supply Curves for the Optimally Managed, Pure Schooling Fishery for Various Discount Rates

Sensitivity Analysis

The open-access equilibrium supply curve is most sensitive to changes in the parameters of the production function; especially for changes in the parameters *b* and *g*. Changes in costs have a moderate effect on open-access supply. The supply curves for the optimally managed fisheries are most sensitive to changes in the biological parameters. They are not very sensitive to changes in the discount rate. The effect of changes in costs on the discounted supply curve is small. For further details see Nøstbakken (2002).

2.2   The Icelandic Cod Fishery

Icelandic cod is mostly found on the Icelandic shelf. In addition, larvae from the Icelandic cod stock drift from Icelandic spawning grounds to the Greenlandic cod stock. When the Greenland cod matures it may return to Icelandic waters to spawn. The Icelandic cod fishery is very important to the Icelandic economy. Throughout the history of the fishery, Iceland has been involved in several disputes, referred to as the Cod Wars, with the United Kingdom over

the rights to harvest the stock. In the final cod war (1975-1976) Iceland went as far as to threaten to close the NATO base at Keflavik, very serious threat to NATO at the time of the Cold War. As a result, the British government agreed not to let its fishermen harvest in the Icelandic EEZ without a specific permission.

In the early 1980s a system of individual transferable quotas (ITQs) was introduced. Annual TAC is determined by a harvest rule that was introduced in the mid-1990s, and adjusted after the 1999 stock assessment, where total catch is a given share of the exploitable biomass (fish aged four and older). There has not been defined a safe biological limit for the stock. With high fishing mortality in recent years and a spawning stock biomass at relatively low levels, the stock is said not to be at a bio-ecologically sustainable level. Although an overfishing threshold has not been defined, several ICES reports consistently consider the fishing mortality of the Icelandic cod as too high (Cook 2002).

Figure 4 shows historical catch and biomass data for the Icelandic cod fishery from 1955 through 2004. From an initial spawning stock biomass (SSB) of 939,000 tonnes in 1955, the stock declined over the next couple of decades and levelled out at about 200,000 tonnes. In 2004, the spawning stock was estimated to 215,000 tonnes. From 1965 onward, the annual landings have been larger than SSB. The difference between landings and SSB has become smaller over the years, and for the last three years shown in the figure, there is almost no difference.
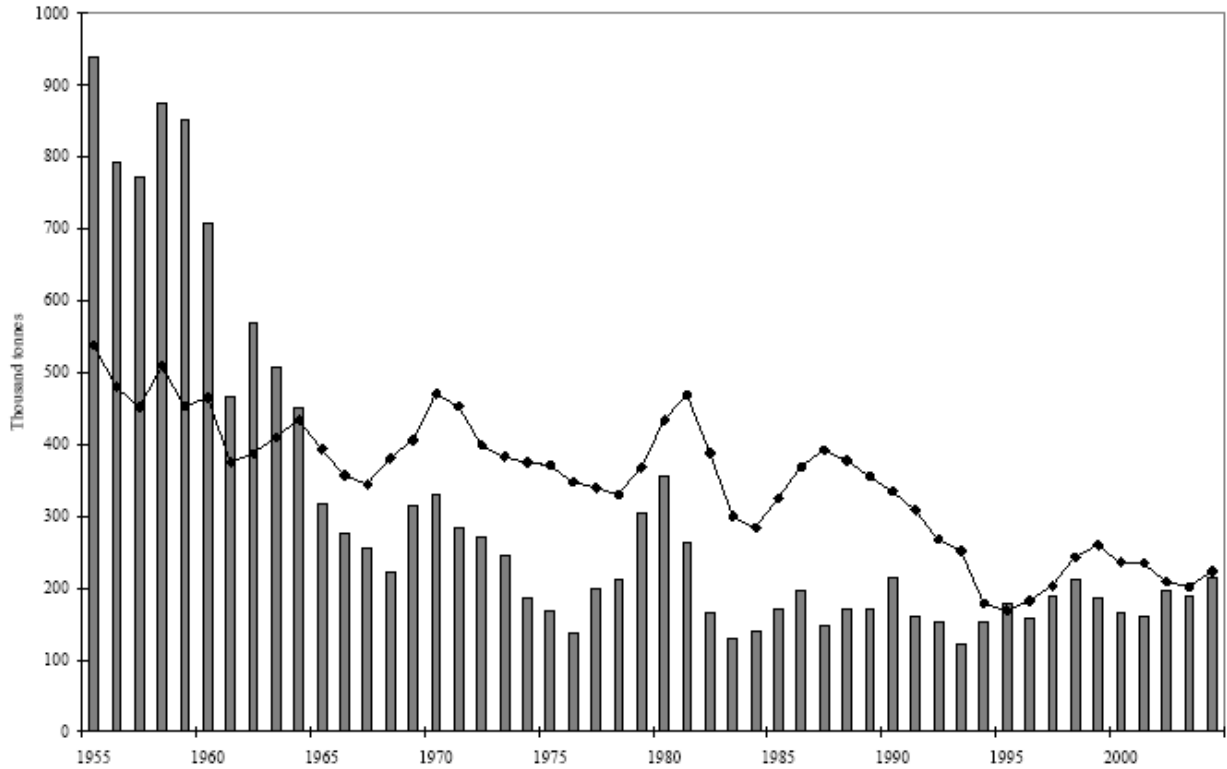
Figure 4. Icelandic Cod: Spawning Stock Biomass and Landings (line), 1955-2004.
Source: ICES.

Parameter values and the model form used to analyse the Icelandic cod fishery is from a recent study by Arnason *et al*. (2004). This article analyses the Danish, Icelandic and Norwegian cod fisheries. In the case of Icelandic cod, stock growth is explained by the logistic growth function with an intrinsic qrowth rate $r = 0.4946$ and a carrying capacity of $K = 2,919,000$ tonnes. Arnason *et al*. (2004) estimated the variable cost function directly based on cost data for the fishing fleet. Harvesting cost is given by the following relationship:

$$C\left(X_t, Y_t\right) = \frac{\alpha Y_t^2}{X_t}. \tag{17}$$

It can be shown that this is a special case of the more general Cobb-Douglas cost function we used for the North Sea herring fishery, with $b = g = \frac{1}{2}$ and $\alpha = \frac{c}{a^2}$ (recall that a is a catchability coefficient and b and g are the output elasticities of effort and stock, repectively). The parameter estimate of the cost function parameter was reported as $\alpha = 17.343$ (1998 Icelandic krónur, ISK), and this will be used here. Finally, Arnason *et al*. (2004) estimate an inverse demand function for Icelandic cod. They find that the slope

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coefficient is not significant and price is therefore given as a constant ($p = 84.215$ measured in 1998 ISK).

Open-access equilibrium

By setting net revenues and change in biomass to zero, we can solve for the open-access biomass and harvest levels:

$$X_\infty = \begin{cases} K\left(1 - \dfrac{p}{\alpha r}\right) & \text{if} \quad p \leq \alpha r \\ 0 & \text{if} \quad p > \alpha r \end{cases}$$

$$Y_\infty = F(X_\infty)$$

$$\text{(18)}$$

If price is above a certain limit ($p > \alpha r$), biomass will be negative if we calculate it by use of the equation $K\left[1 - p/(\alpha r)\right]$. This equation was derived by setting the profit function equal to zero. We therefore add the common-sense constraint that biomass is zero if price is above the given limit. Inserting the parameter values of Arnason *et al.* (2004), we find that under open access the stock is driven to extinction if price is above 8.58 ISK/kg. Given that the price estimate of Arnason *et al.* is about 84 ISK/kg, the results suggest that the stock would have gone extinct under open access.

Optimal management equilibrium

Using the functional forms provided above, it is a relatively simple task to obtain an expression for price by use of equation (7):

$$p = \frac{2\alpha Y}{X} - \frac{\alpha Y^2}{X^2 (r - \delta - 2rX/K)}. \tag{19}$$

In addition, steady-state harvest is again given by the natural growth function $Y = F(X)$.

The Equilibrium Supply Curves for Icelandic Cod

The open access supply curve for Icelandic cod is given in Figure 5. The long-run equilibrium supply of Icelandic cod is seen to be increasing with price until harvest (or supply) reaches the maximum sustainable yield of $MSY = rK/4 = 360{,}934$ tonnes at price

$p = \alpha r/2 = 4.29$. For further price increases, equilibrium supply is decreasing in price until the point where the equilibrium stock is zero.

Comparing equilibrium supply of cod to the one shown in Figure 2 for North Sea herring, there are two main differences. First, in the cod case, long-run supply will be zero because the cod stock is driven to extinction if price is above ISK 8.58 per kg ($p \geq \alpha r [1 - X/K]$).In the herring case, however, supply approaches zero as price approaches infinity. The second difference is that as long as the cod price is positive, the cod stock will be harvested (positive long-run supply). There is consequently no positive price level below which the revenues would be too low to justify harvesting.

The differences in results for cod and herring are due to differences in the cost structure of the harvesting process. For certain parameter values in the cod model, including the parameter values used here, harvesting will always occur as long as price and biomass are positive.
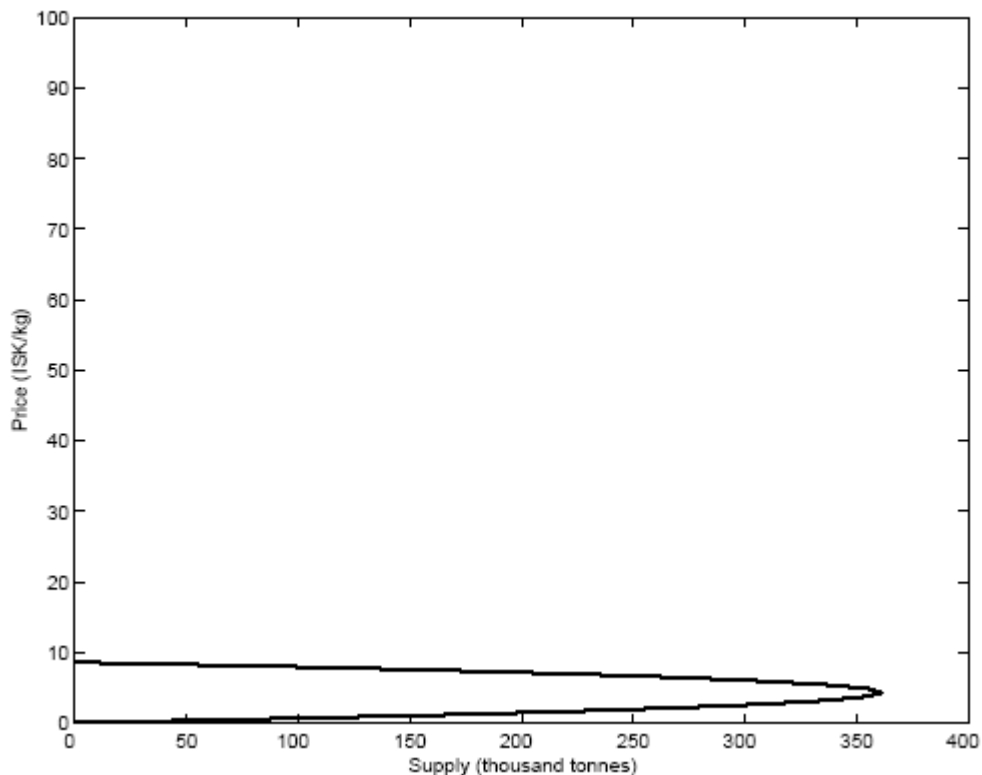

Figure 5. Icelandic Cod: Open Access Supply Curve

While the open access supply curves are seen to be very different, the discounted supply curve for cod, as shown in Figure 6 for discount rate $\delta = 0.06$, has many of the same properties as the discounted supply curve for the herring fishery. First, it has the characteristic backward-bending shape, a result of biological overfishing, as mentioned above. Second, the degree of backward bending is modest. As in the herring case, the degree of backward bending depends on the discount factor. If the fishery manager puts a high value on future harvests (low discount factor), the degree is modest. The less one cares about the future, the higher the degree of backward bending and consequently the extent of biological overfishing.

The major difference in the cod case compared to what we found for North Sea herring is that as long as price is positive, it is optimal to harvest the stock. As in the open-access case, there is no positive price level below which the revenues would be too low to justify harvesting. In optimal management, the stock would be harvested to some degree as long as there is cod left in the sea. This result is due to the assumption made about the cost structure in the model. Although the implication that the stock should be harvested no matter how low the stock level is, may seem a bit peculiar, the current cod price is far above a level where it would be optimal to harvest the stock down to near distinction. Therefore, the optimal supply at more realistic price levels seems to be in line with other analyses (e.g. Arnason *et al*. 2004).

The Icelandic ex-vessel price of cod was increasing in the late 1990s from about 98 ISK/kg in 1997 to about 137 ISK/kg in 1999. This rather large increase in price does not affect the optimal harvest much. Based on these prices, the optimal harvest quantity would have been 350.6 thousand tonnes in 1997 and 349.1 thousand tonnes in 1999. The small difference in harvest despite a fairly large price increase is due to the very modest degree of backward bending of the supply curve in the optimal management case. The actual supply in the late-1990s, was well below this level, with harvests at 203 and 260 and thousand tonnes in 1997 and 1999, respectively. In fact, ever since the early 1990s, the annual landings have been below 300 thousand tonnes. Although the long-run equilibrium supply we have estimated is much higher than actual landings over the past 10-15 years, one should not conclude that it is optimal to harvest more now. Remember that we all the time are referring to the long-run equilibrium, and with the Icelandic cod stock at a very low stock level (cf. Figure 4), the stock is far below the level that would give a sustainable harvest of 350 thousand tonnes.
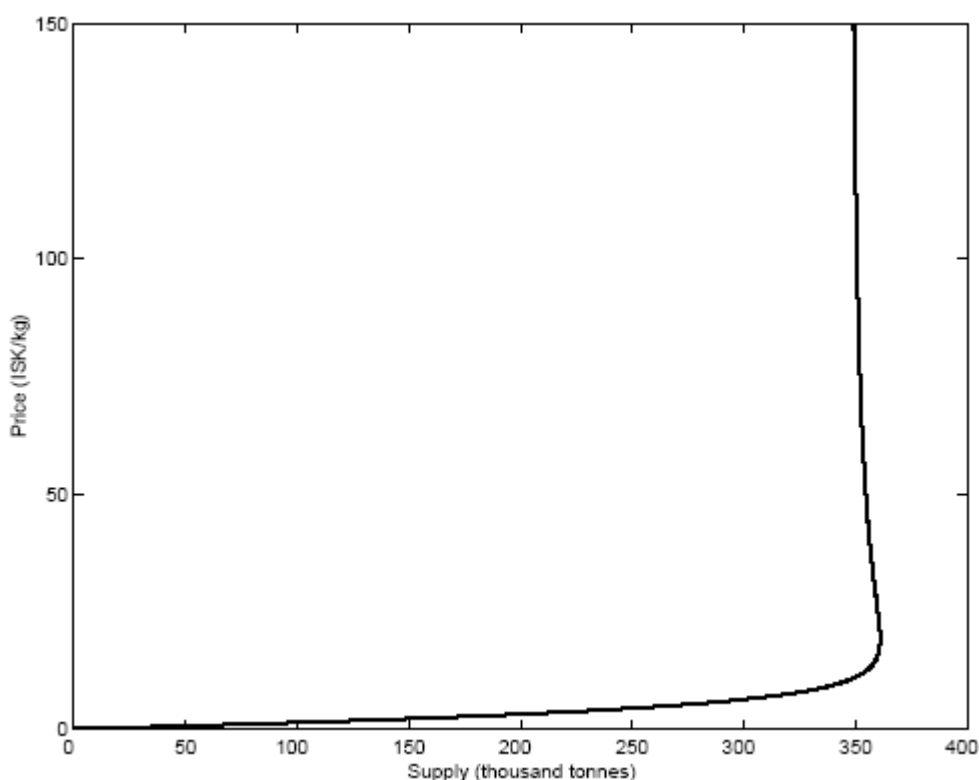
Figure 6. Icelandic Cod: Discounted Supply Curve.

3. SUMMARY

In this paper we have derived and estimated equilibrium supply curves for two fisheries, namely North Sea herring and Icelandic cod, under two different regulatory regimes; open access and optimal management. We have studied two different species with very different biological characteristics. The North Sea herring is a pelagic species found in schools in the sea. The Icelandic cod is a demersal species (it is found near the seabed) and it does not exhibit the schooling behaviour of the herring. Consequently, the methods used to harvest the two stocks are quite different. Based on the particularities of the fisheries in question, different production/cost functions have been used in the bioeconomic models.

Different regulations, both actual and theoretical, were evaluated with respect to effects on supply, stock level, and fishing effort. For North Sea herring, a change in the actual regulations was evident in 1996. From 1996 onwards, the quotas have been relatively small. This has allowed the stock to approach a higher level than the one that maximises rent according to our analysis. Because of this, the annual supply is smaller than in an optimally

managed fishery. However, the supply would have been much smaller under an open-access regime.

In the Icelandic cod case, there is a tremendous difference between the open access and the optimal management case. As long as price is above 8.5 ISK/kg, the stock would be totally depleted under open access. The equilibrium supply under optimal management for price above this level is in contrast relatively close to the maximum sustainable yield of 360 thousand tonnes (as long as price does not explode). It has been pointed out that the current harvest level is far below the optimal equilibrium harvest level. To get closer to our optimal management case, one must allow the stock to grow to a higher level.

This paper represents one of the few empirical analyses of supply functions in the literature. The results have been used to gain a better understanding of the consequences of various regulations of the North Sea herring and Icelandic cod fisheries. The present analyses can be extended in several ways. One possibility would be to re-estimate production functions using updated data and perhaps trying different production function specifications and variables. Another possibility is to combine the supply curves with estimations of demand curves in order to study the market for these species. Similar analysis could also be done for other species.

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