

Working Paper No. 30/02

**Economic evaluation of the fisheries policies
in Denmark, Iceland and Norway:
Some performance indicators**

by

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SNF-project No. 5655
"Komparativ evaluering av fiskeripolitikk under usikkerhet"
The project is financed by the Research Council of Norway

*Centre for Fisheries Economics
Discussion paper No. 8/2002*

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
BERGEN, AUGUST 2002

ISSN 1503-2140

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Economic evaluation of the fisheries policies in Denmark, Iceland and Norway: Some performance indicators.

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Keywords: Comparative efficiency in fisheries, Fisheries management, Optimal feedback controls, Optimal fisheries dynamics.

Abstract

The economic efficiency of the Danish, Icelandic and Norwegian cod fisheries is examined. For this purpose nonlinear aggregate models of these three fisheries are constructed. A particular mathematical approach to calculate the rent maximizing feedback control, i.e. the optimal dynamic harvesting policy as a function of the state variable, is applied. On the basis of this approach, the optimal harvesting policies for each of the three cod fisheries are calculated for years in the past for which biomass and catch data are available. Comparing the calculated optimal harvest and biomass quantities with the actual ones provides a measure of the degree of efficiency in these three cod fisheries. The ratio of optimal versus actual is used as performance indicator.

The comparisons confirm the widely held belief that the cod harvesting policies of these countries have been hugely inefficient in the past. More interestingly, it appears that the inefficiency has been increasing over the last 3-4 decades, even after TAC-regulations replaced open access.

Introduction¹

The primary purpose of this paper is to compare the relative efficiency of the fish harvesting policies of Iceland, Norway and Denmark as they have been in the past. By the term “harvesting policy” we mean the harvesting volume each year. So, efficiency here merely refers to appropriateness of the annual harvesting volumes. It does not, in particular, refer to the relative efficiency of the fishing industries in the three countries.

Iceland, Norway and Denmark are all major fishing nations harvesting a number of fish species. We have chosen to concentrate on cod fishing as this is the single most important fishery, from an economic point of view, in all three countries. The three cod stocks in question are biologically distinct. The period for comparing their cod harvesting policies is 1964-2000. The three nations conduct their cod fisheries in quite different contexts. First, there is a difference in national control over the respective fisheries. Prior to 1976 all three fisheries were characterized by open access. Since the extension of her fisheries jurisdiction to 200 miles in 1976, Iceland has been in virtual sole control of her cod fishery. Norway, on the other hand, shares her cod stock, the Arctic cod, with Russia and must therefore decide on a harvesting policy jointly with Russia. Denmark is only one of several, mainly European Union, countries pursuing the North Sea cod fishery. Since the early 1980s the European Union has set the overall total allowable catch (TAC) for this fishery of which Denmark merely receives a share. Thus, compared to Iceland and Norway, Denmark probably has least control over her cod harvesting policy. In view of these differences in autonomy between the three countries, it is clearly of some interest to investigate whether this shows up in their respective cod harvesting policies. Second, since the mid-1980s, the fisheries management systems employed in the three countries have been quite different. Stated very briefly, Iceland has since 1984 operated a more or less complete ITQ-system in her cod fishery. (Arnason, 1993). Norway has for about the same period managed her cod fishery by means of quasi-

permanent individual quotas (Anon., 1996d). In Denmark, however, the fishery has for the past two decades essentially been managed on the basis of a license limitation program supplemented with very short-term (down to two months) non-permanent, non-transferable vessel quotas (Vestergaard, 1998). Thus, it is clear that the quality of the harvesting rights held by individual companies in these three cod fisheries has differed greatly in recent years. It is often suggested that differences in the fisheries management regime, especially the quality of individual harvesting rights, may influence harvesting strategies (Arnason 1990, Johnson 1995, Scott 1999, Turriss 1999). Therefore, it is of considerable interest to see if empirical evidence of this can be found.

The paper employs an approach that adds empirical content and specific solution procedures to analytical fisheries models in order to generate empirically relevant solutions. More precisely, it suggests statistical estimation of the relationships typically used in analytical fisheries models and then employment of certain mathematical techniques to generate explicit feedback solutions to this class of models. In this way, the current approach attempts to bridge part of the gap between analytical and empirical fisheries models. It is essentially a simple aggregative description of a fishery, just like analytical models, but with empirically estimated relationships, just like empirical models. The same approach has been applied by Grafton, Sandal and Steinshamn (2000) to evaluate Canada's northern cod fishery.

The model presented here is an aggregate bioeconomic model; that is a model that provides rules of thumb for quota management of the stock. This helps to avoid overparameterization of the model and lack of causality in the dynamics. For this reason the parameter estimations should not be judged as econometric analysis but rather as an attempt to keep down the number of parameters in order to make a representative aggregated dynamic model.

Of course, the procedure proposed in this paper does not provide detailed solutions to the fisheries problem. In fact, due to the level of aggregation in the underlying model, it is designed to provide the approximate key attributes of optimal harvesting paths. It is an approach to produce a comprehensive bioeconomic management model. The usefulness lies in its ability to focus on a few global attributes and to provide simple practical characteristics of an optimal management policy. First, in many fisheries, as well as other natural resource use, it is simply not feasible, due to lack of data and other information, to construct a fully-fledged empirical model. Under such circumstances bigger is not better. Second, in many cases, the management capability is simply inadequate to implement detailed management programs anyway. Third, the solution paths generated by our procedure are relatively easy to explain and therefore, perhaps, stand a better chance of being appreciated and adopted. Fourth, the proposed procedure makes it relatively easy to investigate the impact of exogenous changes on the economics of the fishery and optimal harvesting paths. Fifth, the procedure makes it relatively easy to compare, on even footing so to speak, the relative efficiency of the harvesting policies in different fisheries around the world. In fact, this is exactly the use this model is put to later in the paper where the relative efficiencies of the fisheries policies in Denmark, Iceland and Norway are compared.

Although the approach has been developed for fisheries, there is no reason to restrict its use in this way. It can, with only slight modifications, be applied to other use of replenishable natural resources such as water resources, grasslands, forests and the environment in general.

The paper is organized broadly as follows. In section 1 the theoretical model is explained. However, a bit more detailed outline is given in Appendix. In section 2 the model is applied to a comparative study of the fisheries policies in Denmark, Iceland and Norway. Finally, section 3 contains a brief discussion of the main results of the paper.

Theoretical model

This section sketches the theoretical model that is used to determine an optimal harvesting policy.² The objective is to discover the time path of harvest that maximizes the following functional:

$$(1) \quad \int_0^{\infty} e^{-\delta t} \Pi(h, x) dt$$

$$\text{subject to } \dot{x} = f(h, x), \quad x(0) = x_0, \quad \lim_{t \rightarrow \infty} x(t) = x^* > 0$$

where x represents the fish stock biomass, h the flow of harvest, Π net revenues³ and $f(.,.)$ is a function representing biomass dynamics. Dots are used to denote time derivatives, and δ is the discount rate. The symbol x_0 represents initial biomass and x^* some positive (steady state) biomass level to which the optimal program is supposed to converge.⁴ The functions Π and f can in principle be any functions as long as the second-order conditions are fulfilled. In the following it is assumed that the functions fulfill the Mangasarian Sufficiency Theorem for infinite horizon (Theorem 13 in Seierstad and Sydsæter (1987)).

In the following applications we use the optimal feedback procedure developed and described in Sandal and Steinshamn (2001), and also applied by Grafton, Sandal and Steinshamn (2000). A short outline of this method is also given in Appendix. By an optimal feedback control is meant optimal harvest (the control) given as a direct function of the stock biomass (the state). The clue with this procedure, compared to traditional optimal control theory, is that the costate variable in the Hamiltonian is eliminated, using the maximum principle, instead of elaborated upon. This, as it turns out, makes it much easier to derive

feedback control laws for optimal harvest. The usefulness of feedback control laws is emphasized by Conrad and Clark (1987) and Clark (1990) among others. The result of the model is a mathematical rule that prescribes optimal harvest as a function of the prevailing stock:

$$h_t^{opt} = h(x_t).$$

Application: The performance of the Danish, Icelandic and Norwegian cod fisheries

In this section the above approach is employed to throw some light on the relative efficiencies of the cod fisheries of Denmark, Iceland and Norway. In particular, the approach will be used to provide estimates of how close to (or distant from) the optimal path the actual utilization of the cod stocks of the three nations has been. For this purpose the parameters of the net revenue and growth function that form the building blocks of the aggregate fisheries model will be estimated. With these parameters the feedback method will be employed to calculate the optimal cod harvest for each of the three countries every year. Finally, comparing the calculated optimal paths with the actual ones provides an estimate of their relative efficiencies. In this section a zero discount rate is used in order to emphasize sustainability of the activity. As long as the intrinsic growth rate is large compared to the discount rate (which is the case here) positive discounting only implies a small alteration in the optimal harvest paths, see Sandal and Steinshamn (2001).

The empirical model

First the details of the biological submodel will be given.

Biological dynamics

It is assumed that the instantaneous change in stock biomass equals natural growth less harvest:

$$\frac{dx}{dt} \equiv f(x, h) = g(x) - h$$

where $g(x)$ is a surplus growth function. It is not possible to estimate $g(x)$ directly, because the available data is in discrete time. Consequently, we employ a discrete approximation in order to estimate the surplus growth. For Norway the following functional form (generalized logistic) gave the best fit

$$g(x) = rx^2 \left(1 - \frac{x}{K} \right)$$

whereas for Denmark and Iceland the logistic function,

$$g(x) = rx \left(1 - \frac{x}{K} \right),$$

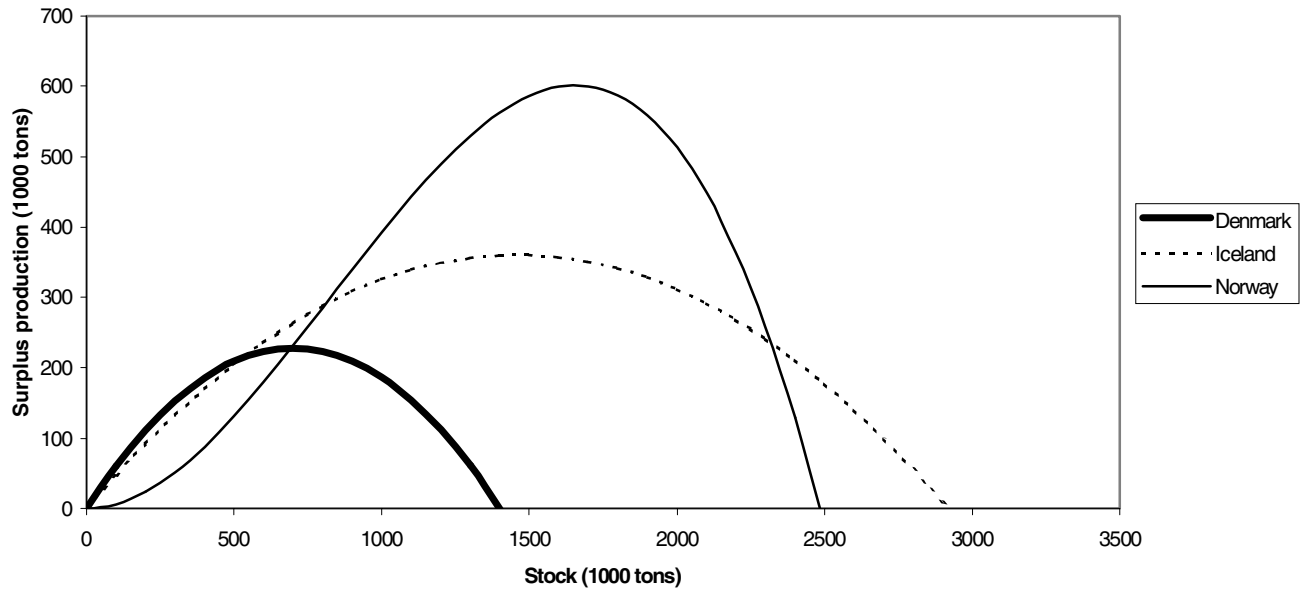
yielded the best fit. In both cases K is the carrying capacity of the stock (Clark, 1990). The estimations were performed using NLREG and EViews⁵. The results of the estimations are shown in Table 1.

Table 1. Statistical properties of the biological growth functions. K is 1000 tons.

	Function	Parameters	t-statistics	Other statistics ⁶
Denmark (n = 36)	$rx\left(1 - \frac{x}{K}\right)$	r=0.652155 K=1,402	4.87 6.03	R ² =0.11 F=4.31 DW=2.30
Iceland (n = 45)	$rx\left(1 - \frac{x}{K}\right)$	r=0.4946 K=2,919	8.53 3.83	R ² = 0.25 F=14.67 DW = 1.52
Norway (n = 22)	$rx^2\left(1 - \frac{x}{K}\right)$	r = 6.57E-4 K = 2,485	11.65 23.73	R ² = 0.51 F = 23.16 DW = 1.67

For Denmark the whole North Sea stock is used as basis for the estimation. Data for stock and landings are taken from Anon (1997a). For Norway we use data for the Arctic cod stock from Anon (2001). For Iceland the relevant data relating to estimation of a growth function is given in Anon (1998a, 1998b and 2001b). The differences in scale of the respective fisheries are illustrated in Figure 1. Notice that the Icelandic stock is significantly larger and less productive than the Norwegian stock. If the differences in costs and prices are not to extreme one should expect a higher moratorium level and steeper optimal harvest path for Iceland. This qualitative behaviour is indeed reflected in the calculated optimal paths.

Figure 1. The biological growth function for Denmark, Iceland and Norway



Economic model

The generic net revenue function employed in the empirical model is:

$$\pi(h, x) = p(h, x)h - C(x, h).$$

where $p(h, x)$ represents the (inverse) demand function for landed cod, and $C(h, x)$ is the cost function associated with the harvest process. All prices are real prices deflated by the respective countries' consumer price index. In reality the prices also change over time due to changes in taste, etc. This calls for a non-autonomous analysis, which is beyond the scope of this paper.

Several forms of the demand and cost functions were estimated for the three countries. Due to differences in data availability and industry structure between the three countries it is most convenient to discuss the estimation of these functions for each country in turn.

Denmark

Using data from Anon (1991) and Anon (1996b) an inverse demand function for cod landings of the form $p(h) = a - bh$ was estimated. Adjusted for autocorrelation it turned out that the slope coefficient was statistically insignificant. We therefore proceed on the assumption of a constant price of cod landings of DKr 10.4. The estimation results are summarized in Table 2. A likely reason for this result is that Danish cod landings are quite small relative to the total supply in the North Sea market area, and consequently the price is not very sensitive to variations in Danish landings.

Because we only have data for two years in Anon (1996a), we have calibrated a variable cost function (see Howitt 1995 for an example). We have calibrated on the whole North Sea stock but have used the Danish part of the catches in The North Sea. The calibration gives the following result:

$$C(h, x) = 29.618 h^2/x$$

The Danish net revenue function thus reads:

$$\pi(h, x) = 10.4h - 29.618 h^2/x,$$

when h and x are measured in metric tons.

Table 2. Statistical properties of the estimated demand functions. Estimation procedure: OLS, except GLS for Iceland.

	Function	Parameters	t-statistics	Other statistics ⁷
Denmark (n=17)	$p(h) = a$	10.40	11.23	$R^2=0.0$ F=10.80 DW=2.07
Iceland (n=48)	$p(h) = a$	84.215	10.4	$R^2=0.88$ F= 337.3 DW=2.21
Norway (n = 33)	equation (2)	$a = 9.52$ $b = -2.07E-6$ $c = -11763$	20.50 -6.73 -4.40	$R^2 = 0.58$ F = 23.28 DW = 1.18

Iceland

The inverse demand function for cod landings, $p = a - bh$, was estimated using monthly data in 1996 and 1999 (Anon 1998b, Anon 1999 and Anon 200b). A generalized least squares estimated method with autocorrelation was used, and it turned out that the slope coefficient is statistically insignificant. On the other hand a dummy variable (unity in April 1997, otherwise zero) was found to be needed. As a result, we proceed on the assumption of fixed price of cod landings, which was estimated to be ISK 84.215 per kg. of landings (1998 prices). The key estimation results are further summarized in Table 2.

The reason for this apparent price inflexibility may be that during the data period most Icelandic landings of cod took place within vertically integrated fish harvesting and processing firms with the landing price of cod to a great extent simply representing a transfer

price between two stages of the overall operation. In addition to this, many of the independent harvesting operations supplied their catches of cod to processing firms according to fixed price contracts. For these reasons, and in spite of the emergence of auction markets for fish landings in recent years, the wetfish price of cod was almost completely insensitive to short term variations in supply.

The cost function, $C(h) = a \frac{h^2}{x}$, was estimated using a combination of cross-section and time series data, i.e. a balanced panel data, on variable costs. The main data source was Anon (1998c). The time period was 1985 to 1995, and the total number of observations was 307. The cost data are in fixed 1998-prices. A generalized least squares (GLS) estimation technique based on White's heteroscedasticity-consistent method was employed. The key estimation results are:

$$C(h, x) = 17.343 h^2/x,$$

with more details to be found in Table 3.

The Icelandic net revenue function therefore is:

$$\pi(h, x) = 84.215 \cdot h - 17.343 h^2/x$$

where h and x are measured in 1000 tons.

Norway

The inverse demand function for Norwegian cod landings was estimated on the basis of annual data on real prices and landings obtained from Anon (2001a). The following form gave the best statistical properties:

$$(2) \quad p(x, h) = \begin{cases} a + [bx + cx^{-2.2}]h & \text{if } x > 1330 \\ a + cx^{-2.2}h & \text{if } x < 1330. \end{cases}$$

where a , b and c are parameters. The inclusion of the stock in the inverse demand function may seem a bit odd, but we must remember that buyers of landed fish are highly professional buyers who probably take stock estimates into account.

The key estimation results are listed in Table 2. The data are assumed to represent the demand function as the supply function is exogenously given through a binding TAC regulation scheme with little or no alternative harvest outlets.

Annual data from Anon (1995, 1996c, 1997d, 1998d, 1999a, 2000) are used to estimate a variable cost function. Variable costs are total variable costs for the trawlers multiplied by the share of cod in total harvest and deflated with the consumer price index (1998=100). The following simple functional form gave the best fit:

$$C(h, x) = \alpha \frac{h}{x}$$

and the parameter α was estimated to 8824 (see Table 3). Therefore the Norwegian net revenue function is:

$$\pi(x, h) = \begin{cases} ah + [bx + cx^{-2.2}]h^2 - 8824 \frac{h}{x} & \text{if } x > 1330 \\ ah + cx^{-2.2}h^2 - 8824 \frac{h}{x} & \text{if } x < 1330. \end{cases}$$

when h and x are measured in 1000 metric tons.

Table 3. Statistical properties of the estimated cost functions. Estimation procedure: Norway OLS, Iceland GLS.

	Function	Parameters	t-statistics	Other statistics ⁸
Denmark ⁹	$C(x, h) = \alpha \frac{h^2}{x}$	$\alpha = 29.618$		
Iceland ($n = 307$)	$C(x, h) = \alpha \frac{h^2}{x}$	$\alpha = 17.343$	19.49	$R^2 = 0.86$
Norway ($n = 6$)	$C(x, h) = \alpha \frac{h}{x}$	$\alpha = 8824$	110.02	$R^2 = 0.99$ DW = 2.57

Comparative efficiency

Having completed the construction of our fisheries model we are now in a position to assess the relative efficiency of the cod harvesting policies followed by the three countries in the past. For this purpose two main indicators are employed: (i) the actual versus optimal stock ratio, and (ii) the actual versus optimal harvest ratio. The target reference value for both indicators are one.

It may be noted that the individual country's net revenue functions are expressed in different currencies and price levels. Moreover, they relate to widely different average biomass levels as illustrated in Figure 1. This, however, does not pose problems for comparison as the performance indicators to be used are dimensionless.

The comparative results are primarily presented by means of diagrams. This has the advantage of conveying all data points simultaneously. However, in order to facilitate efficiency comparison for the whole period, simple numerical measures have been devised.

The one used to assess the performance of the stock policy is:

$$\eta = \frac{\sum_{t=1}^T \eta_t}{T} \in [0, \infty)$$

where T is length of the period and $\eta_t = \frac{x_t^{act}}{x^*}$, where x_t^{act} is the actual stock at time t and x^* is the optimal steady state.

Obviously, the most desirable value of η is unity; $\eta < 1$ suggests an economically overexploited stock and $\eta > 1$ suggests underexploitation of the stock.

To assess the performance of the harvest policy we use¹⁰:

$$\varphi = \frac{\sum h_t^{act}}{\sum h_t^{opt}} \in [0, \infty),$$

where h_t^{opt} is the optimal level of harvest at time t (which may be zero) and h_t^{act} the actual harvest at time t . Optimal harvest at each point of time is calculated using the optimal feedback rule, i.e. $h_t^{opt} = h(x_t^{act})$. Obviously, $\varphi = 1$ indicates a perfectly efficient harvesting policy; $\varphi > 1$ indicates economic overharvesting and $\varphi < 1$ economic underharvesting. Both these relations are performance indicators and, as such, independent of the scale of the fisheries.

Consider first the performance of the cod stock policy in each country. This is illustrated in figures 2 – 4. In these figures the actual biomass relative to the optimal one (the η -measure) is presented. In addition a horizontal reference line corresponding to the fishing moratorium level (where it is optimal to cease fishing) is drawn in the diagrams.

Figure 2. Denmark: Stock relative to optimal steady state

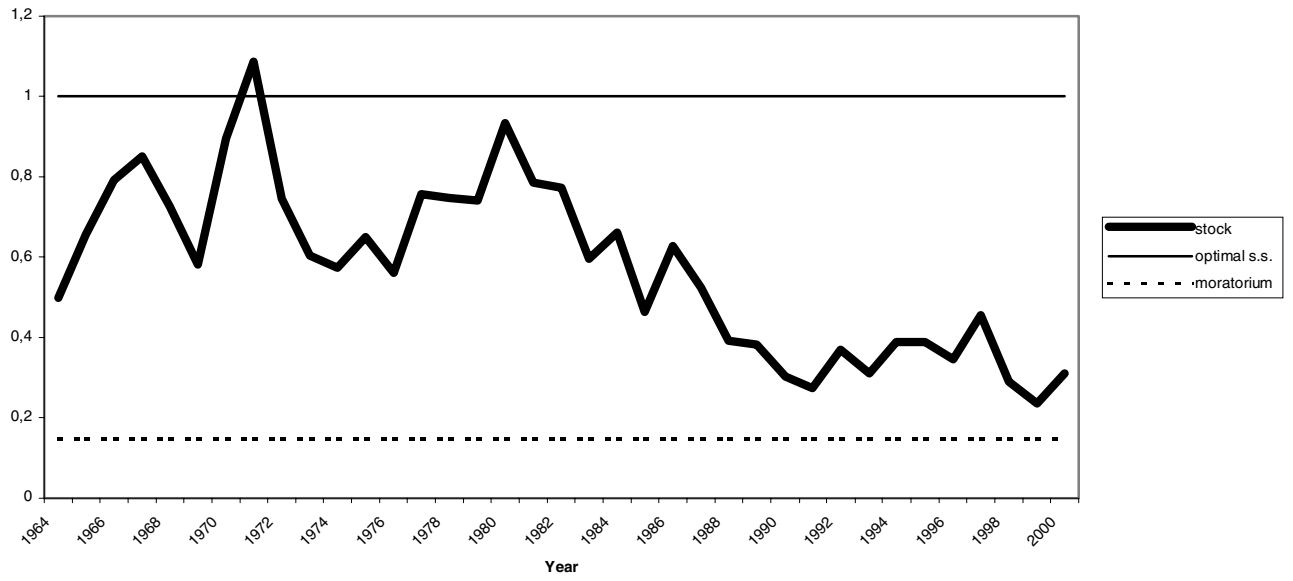
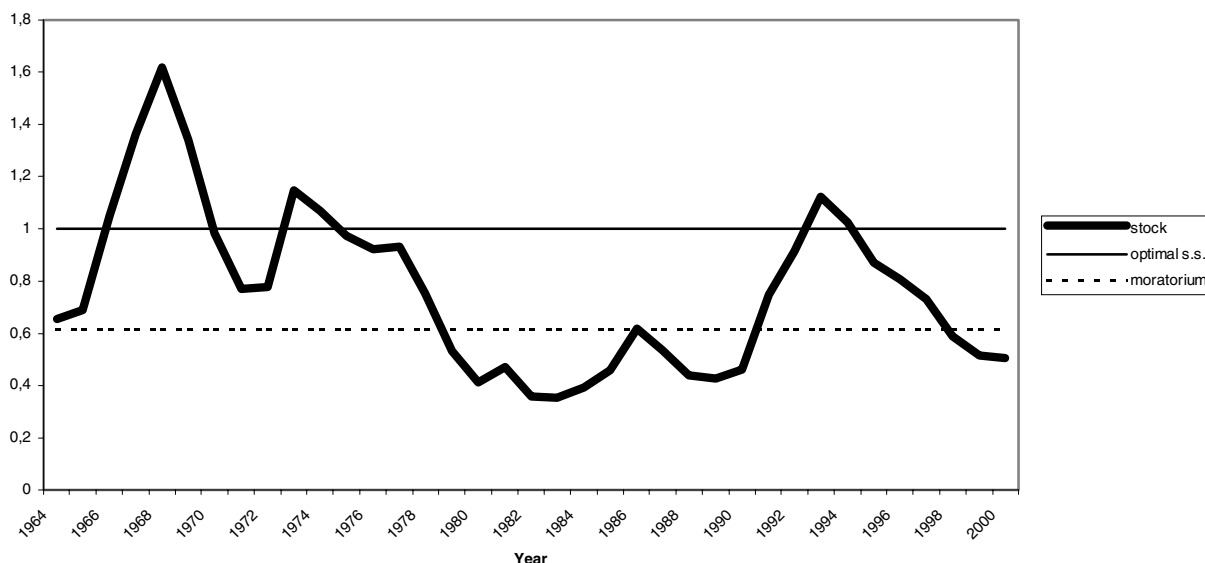


Figure 3. Iceland: Stock relative to optimal steady state



Figure 4. Norway: Stock relative to optimal steady state



As illustrated in Figures 2-4, the cod stock biomass for these three countries is far below the economically optimal level (i.e. unity in the diagrams) for most of the period. Moreover, all three cod stocks exhibit a clear downward trend relative to the optimal level over time. Thus, the model confirms the general view that the North-Atlantic and North Sea cod stocks are overexploited, and the overexploitation is getting worse. There is no sign of any change in this trend after TAC-regulations were introduced in the late seventies.

In Denmark the cod stock never falls below the moratorium level. However, the stock only manages to exceed the optimal equilibrium level once, namely in 1971. In Iceland, the cod stock is above the calculated optimal equilibrium level both in the late sixties and in the late seventies. Since then, however, the stock development has generally been downhill, and after 1982 the stock has been below the fishing moratorium level. It should be noted, however, that due to the nature of the estimated Icelandic growth function, this moratorium occurs at a higher stock level than for Norway and much higher than Denmark. It reflects that the Icelandic stock is larger and less productive than the Norwegian (as seen from their carrying capacities and maximal growth). The Danish stock is relatively small and productive.

The development of the Norwegian cod stock is quite similar to the Icelandic one. It begins with a good period in the mid-sixties when the stock is well above the optimal steady state. Thereafter it declines, especially in the 1970s, and languishes at very depressed levels in the 1980s getting below the fishing moratorium level.

For the period 1964-2000 the average η -measure is closest to the optimal level for Norway ($\eta = 0.77$). The corresponding η -measures are 0.68 for Iceland and only 0.57 for Denmark. Looking at the period with TAC-regulations (1978 – 2000) the rankings of the countries remain the same but the average performances have decreased for all three, indicating, as already noted, that TAC-regulations have had no significant positive effect on stock performance in any of these countries. This is documented in Table 4.

Table 4. Cod biomass relative to the optimal (η -measures).

	Common data period 1964 - 2000	Period with TAC-regulation 1978 – 2000
Denmark	0.57	0.49
Iceland	0.68	0.60
Norway	0.77	0.61

Let us now turn to the performance of the *harvest* policies (the ϕ -measure) in each of the three countries.¹¹ From Figures 5 – 7, which illustrate actual and optimal harvest against the stock together with the surplus production function, it is evident that the harvesting for all three cod stocks have been severely excessive. The harvesting performance indicators are presented in Table 5.

In all three countries, the cod harvesting policies have been severely excessive. The Icelandic case is the worst with Norway not far behind. The degree of overexploitation has also significantly increased in both Iceland and Norway during the latter part of the period. Compared to the other two countries Denmark has operated the most stable harvesting policy, but, unfortunately, it has been stable overexploitation. By contrast, Iceland's harvesting policy is the most volatile. It features some years of close to optimal harvesting and even underharvesting in the early period. But Iceland also has the most severe cases of excessive overharvesting, i.e. substantial harvest when, according to the calculations of this paper, a harvest moratorium should have been imposed..

For the common data period (1964 - 2000), the average exploitation rate relative to the optimal is highest for Iceland ($\phi = 3.71$). This means that during this period, the cod harvest in Iceland has on average been more than three times the optimal one. In Denmark and Norway the average levels of overharvesting have been lower, 2.60 and 2.73, respectively. For the period with TAC-regulation things become even worse. The ranking of the countries remains the same, but the degree of overexploitation has increased in all three.

Table 5. Efficiency of the cod harvesting policies (ϕ -measures)

	Common data period 1964 - 2000	Period with TAC-regulation 1978 – 2000
Denmark	2.60	2.96
Iceland	3.71	5.74
Norway	2.73	4.13

Figure 5. Denmark: Growth function and actual and optimal harvest against stock

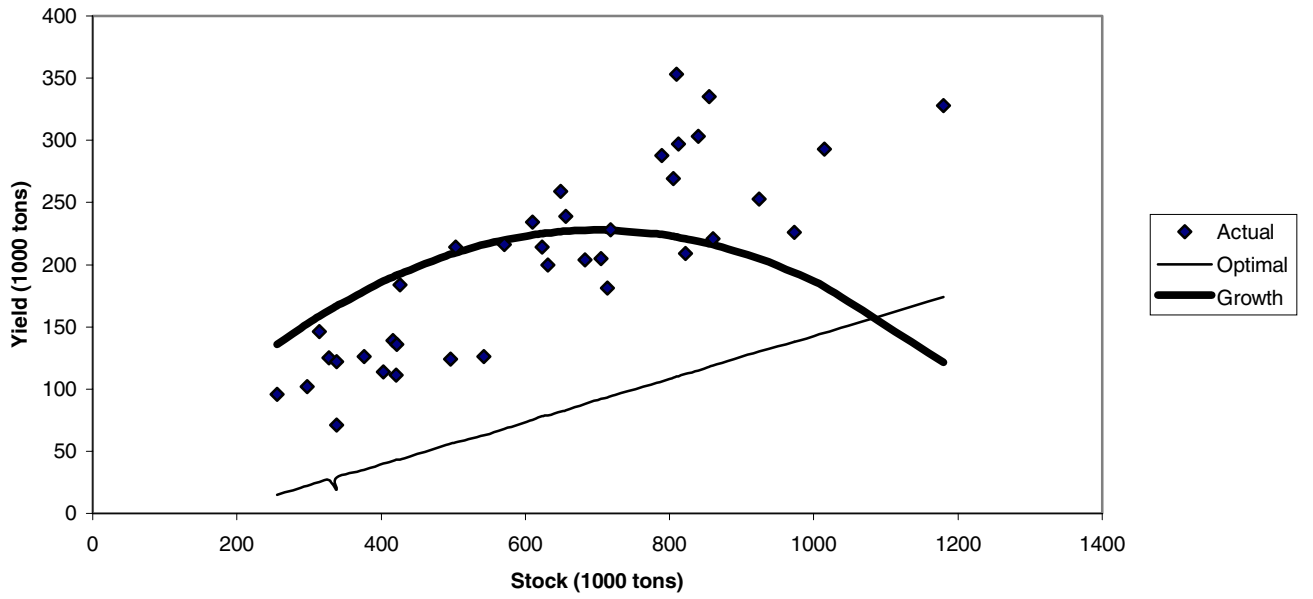


Figure 6. Iceland: Growth function and actual and optimal harvest against stock

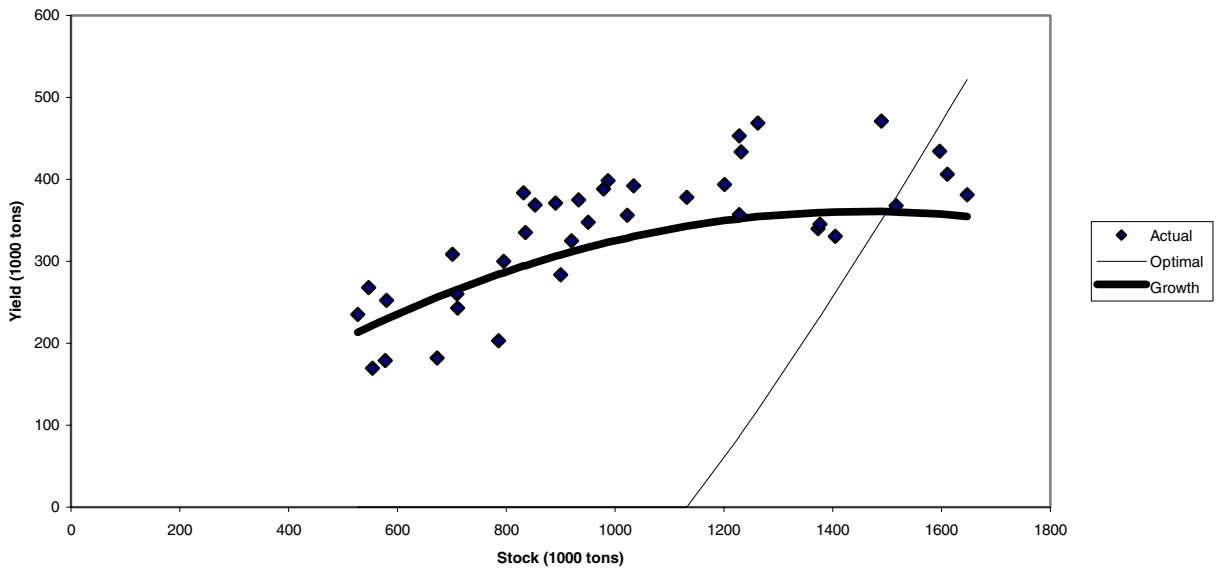
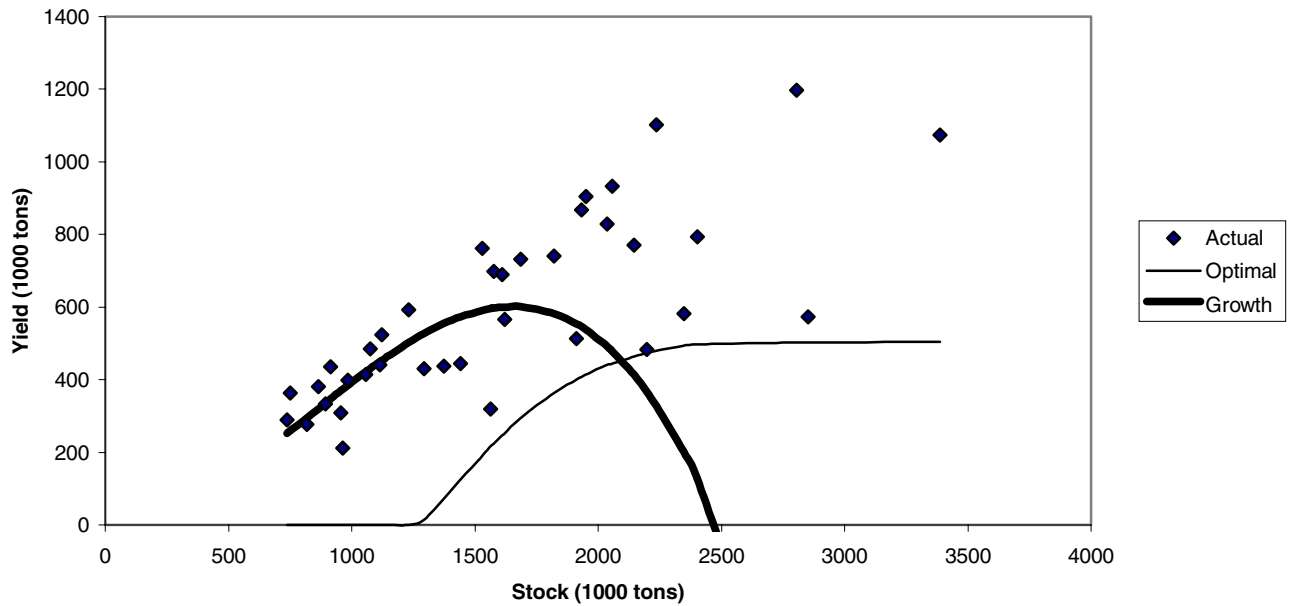


Figure 7. Norway: Growth function and actual and optimal harvest against stock



From Figures 5 - 7 it is seen that the optimal harvest paths are close to straight lines for Denmark and Iceland but is quite curved for Norway. This difference is due to the estimated price-harvest relationship for Norway. It is also interesting to note that, for Denmark and Norway, the actual harvest policies are close to the optimal policies shifted upward by a constant. Thus, the actual harvest policies for these countries have had roughly the same slope as the optimal policy. This may be partly explained by a high time preference. For Iceland, on the other hand, the actual harvest policy has a different slope from the optimal one. In the case of Iceland, the actual harvest looks like an attempt to have a constant harvest rate irrespective of the stock size.

Discussion

This paper contributes, as we see it, primarily in two different ways. First, the paper demonstrates that it is now quite feasible – in fact relatively easy - to calculate optimal feedback policies for renewable resource extraction on the basis of simple aggregate models.

Secondly, the paper provides quantitative information about the economic efficiency, or rather inefficiency, of the cod fisheries in Denmark, Iceland and Norway in recent decades.

Optimal feedback policies calculated on the basis of simple aggregate models can be useful in a variety of ways: First, obviously, such calculations can be employed as a quick check on the efficiency of existing policies. Second, such calculations can provide preliminary estimates of optimal paths and the accompanying economic benefits. Depending on the deviation from the current situation and the magnitude of the potential gains, this can then be used to judge whether a more in-depth study or even a policy change are justified. Third, as in this paper, deviations from calculated optimal paths can be used for international efficiency comparisons and, possibly, to throw light on the relative efficacy of different fisheries management regimes. It has been an aim to focus on a few main quantities encompassing the key features of the stocks.

Our comparative study of the three cod fisheries is perhaps more striking in terms of the similarities it uncovers rather than the differences. For all three countries the efficiency of their cod fisheries, measured as the ratio between actual and optimal levels, appears to have been quite low. Moreover, for all three countries this efficiency shows a declining trend since the 1960s. This trend is, of course, in broad accordance with the prediction of fisheries economics for open access fisheries and therefore as expected. What is mildly surprising, however, is that in spite of much greater national control over the cod fisheries since the 1970s (at least in Iceland and Norway) and greatly more extensive fisheries management since then, there are very few signs of a reversal in this trend of declining efficiency. This is reflected by the fact that the performance indicators unequivocally are worse in the period from 1978 onwards, with TAC-regulations, than it was before 1978.

During the last decade or so the cod fisheries in the three countries have been subject to somewhat different fisheries management systems. The cod fishery in Denmark is managed

on the basis of the Danish share of the total allowable catch and short-term vessel quotas (up to 3 month) (Vestergaard, 1998). The Norwegian cod fishery has been managed on the basis of individual but nontransferable quotas (Anon., 1996d) and the Icelandic cod fishery has been managed primarily on the basis of transferable quotas (Arnason, 1996). The differential effects of these management systems, if any, do not show up in our efficiency measures. These measures, of course, are restricted to aggregate harvest rates and biomass levels, so these results do not exclude different economic returns in the fisheries deriving from the different operational efficiencies of the respective industries. Nevertheless, it is interesting to note that to the end of our data period (2000), the theoretical superiority of individual quota systems (see e.g. Hannesson 1994) does not seem to be reflected in the build up of cod biomass towards the optimal level, neither in Iceland nor Norway. It may, of course, be the case, that this impact of the individual quota systems in Iceland and Norway — really only in effect since about 1990 — is yet to emerge.

Our initial hypothesis that the countries with the highest degree of autonomy have the highest incentives to manage their fisheries well, is to a certain extent supported by the η -coefficient measuring stock-exploitation. Denmark, who has the lowest degree of autonomy, also has the lowest η -value. The hypothesis is, however, not supported by the ϕ -coefficient measuring harvest efficiency, as the Denmark has the lowest value here too, indicating the lowest degree of harvest overexploitation.

Appendix

The current value Hamiltonian, corresponding to problem (1), may be written as:

$$H = H(h, x, \lambda) = \Pi(h, x) + \lambda f(h, x),$$

where λ is the current value costate variable. Assuming an interior solution (i.e. positive biomass and harvest), the necessary first-order conditions for solving the maximization problem (Kamien and Schwartz, 1991) include:

$$\begin{aligned} H_h &= 0, \\ \dot{\lambda} &= \delta \cdot \lambda - H_x. \end{aligned}$$

Upon differentiating the Hamiltonian function with respect to time, these conditions, combined with the dynamic constraint in (1), yield¹²

$$(A1) \quad \dot{H} = \delta \cdot \lambda \cdot \dot{x}.$$

The interior optimum condition, $H_h = 0$, implies that the costate variable, λ , can be rewritten as a function of x and h :

$$\lambda = -\frac{\Pi_h}{f_h} \equiv \Lambda(h, x).$$

As this is a known function (provided the functions Π and f are known), it can be used to eliminate the costate variable, λ , from the problem. More to the point, it is now possible to

define the following new function (different from the Hamiltonian as a function but always equal to it in value):

$$(A2) \quad P(h, x) = \Pi(h, x) + \Lambda(h, x)f(h, x)$$

For fisheries management purposes it is extremely useful to be able to express the optimal harvest at each point in time as a function of the fish stock biomass at that time. Let us refer to this as the function $h(x)$. In the optimal control literature, this is referred to as a feedback control (Seierstad and Sydsæter 1987, p. 161, Kamien and Schwartz 1991, p. 262). So, we seek the feedback control, $h(x)$, for problem (1). Inserting this unknown function into (A2) and differentiating with respect to time yields:

$$\dot{P} = \left(\frac{\partial P}{\partial x} + \frac{\partial P}{\partial h} \frac{\partial h}{\partial x} \right) \cdot \dot{x}.$$

But by construction $\dot{P} \equiv \dot{H}$. Hence, by (A1) we obtain the first-order differential equation that can be used to determine the feedback control:

$$(A3) \quad \frac{dP}{dx} \equiv \frac{\partial P}{\partial x} + \frac{\partial P}{\partial h} \frac{\partial h}{\partial x} = \delta \cdot \Lambda(h, x).$$

Solving (A3) or, if that is more convenient, (A2) for the harvest, h , yields the desired feedback control.

References:

Anon (1991):” Fiskeristatistisk Årbog

Anon (1995):”Lønnsomhetsundersøkelser for fiskefartøyer: 13 m 11 og over. 1995”

(Fiskeridirektoratet, Bergen).

Anon (1996a):”Account for fishery”, Danish Institute of Agriculture and Fisheries

Anon (1996b):”Fiskeristatistisk Årbog, Danmarks Statistik.

Anon (1996c):”Lønnsomhetsundersøkelser for fiskefartøyer: 13 m 11 og over. 1996”

(Fiskeridirektoratet, Bergen).

Anon (1996d): “Forskrift av 11.10.96 om einingskvoteordninga i den norske

torsketrålarflåten” (Fiskeridirektoratet, Bergen) [in Norwegian].

Anon (1997a)”Report of the Working Group on the assessment of Demersal Stocks in the

North Sea”, ICES CM 1998/Assess: 7.

Anon (1997b) "Útvegur 1996". The Fisheries Association. Reykjavík.

Anon (1997d):”Lønnsomhetsundersøkelser for fiskefartøyer: 8 m 11 og over. 1997”

(Fiskeridirektoratet, Bergen).

Anon (1998a): “State of Marine Stocks in Icelandic Waters 1997/98”. Marine Research

Institute. Reykjavík.

Anon (1998b) "Útvegur 1997". The Fisheries Association. Reykjavík.

Anon (1998c): Industry report, nr. 56. National Economic Institute. Reykjavik.

Anon (1998d):”Lønnsomhetsundersøkelser for fiskefartøyer: 8 m 11 og over. 1999”

(Fiskeridirektoratet, Bergen).

- Anon (1999) *Útvegur 1998*. Statistics Iceland. Reykjavik
- Anon (1999a):”Lønnsomhetsundersøkelser for fiskefartøyer: 8 m 11 og over. 1997”
(Fiskeridirektoratet, Bergen).
- Anon (2000):”Lønnsomhetsundersøkelser for fiskefartøyer: 8 m 11 og over. 1997”
(Fiskeridirektoratet, Bergen).
- Anon (200b) *Útvegur 1999*. Statistics Iceland. Reykjavik
- Anon (2001):”Report of the Arctic fisheries Working Group”, ICES, Copenhagen.
- Anon (2001a):”Statistical Yearbook of Norway”, Statistics Norway, Oslo.
- Anon (2001b): “State of Marine Stocks in Icelandic Waters 1999/2000”. Marine Research
Institute. Reykjavík.
- Arnason, R. 1990. Minimum Information Management in Fisheries. *Canadian Journal of
Economics* 23:630-53.
- Arnason R. 1993. The Icelandic ITQ System: A Descriptive Account. *Marine Resource
Economics* Vol. 8(3), pp. 201-218.
- Arnason, R. 1996. On the ITQ Fisheries Management System in Iceland. *Review in Fish
Biology and Fisheries* 6, 1996, pp. 63-90.
- Clark, C.W. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable
Resources*. Wiley, New York
- Conrad, J.M. and Clark, C.W., 1987, *Natural Resource Economics: Notes and Problems*,
Cambridge University Press, Cambridge.
- Gordon, H.S. 1954. The economic theory of a common property resource: the fishery *Journal
of Political Economy* 62:124-42

- Grafton, R.Q., Sandal, L.K. and Steinshamn, S.I., 2000, How to Improve the Management of Renewable Resources: The Case of Canada's Northern Cod Fishery. *American Journal of Agricultural Economics* 82: 570-580.
- Hardin, G. 1968. The Tragedy of the Commons. *Science* 162:1243-47
- Hannesson, R. 1994. *Bioeconomic Analysis of Fisheries*, Fishing News Books.
- Howitt, R.E., 1995, A calibration method for agricultural economics production models, *Journal of Agricultural Economics*, 46: 147-159.
- Johnson, R. 1995. The Implications of Taxing Quota Value in an Individual transferable Quota Fishery. *Marine Resource Economics* 10:327-40.
- Kamien, M.I. and N.L. Schwartz, 1991, *Dynamic optimization: the calculus of variations and optimal control in economics and management*, Amsterdam, North-Holland.
- Sandal, L.K. and S.I. Steinshamn 1997. A Stochastic Feedback Model for Optimal Management of Renewable Resources. *Natural Resource Modeling* 10: 31-52.
- Sandal, L.K. and S.I. Steinshamn 2001. A Simplified Approach to Optimal Resource Management, *Natural Resource Modeling* 14: 419 – 432.
- Scott, A.D. 1999. *Introducing Property in Fisheries Management*. A paper submitted at the FAO Conference FishRights99, Fremantle Australia. Forthcoming in the proceedings.
- Seierstad, A. and K. Sydsæter. 1987. *Optimal Control Theory with Economic Applications*. North-Holland, New York.
- Turris, B. 1999. *A Comparison of British Columbia's ITQ Fisheries for Groundfish Trawl and Sablefish: Similar Results from Programs with Differing Objectives, Designs and Processes*. A paper submitted at the FAO Conference FishRights99, Fremantle Australia. Forthcoming in the proceedings.

Vestergaard, N. 1998. Property Rights Based Regulation of Fishery: Applications and Theory.

Ph.D. Thesis No.77. University of Copenhagen, Institute of Economics.

White, H.1980. A heteroscedasticity-consistent Covariance Matrix Estimator and Direct Tests

for Heteroscedasticity. *Econometrica* 48: 189-205.

Endnotes

¹ We would like to thank Sveinn Agnarsson and Frank Jensen for valuable research assistance in preparing this article. Financial support from the Nordic Council of Ministers is gratefully acknowledged.

² The model can also be generalized to include general stochastic processes (Sandal and Steinshamn, 1997).

³ Net revenues are simply defined as economic profits, i.e. revenues in excess of current operation costs (outlays). This is all on cash flow basis.

⁴ Indeed, the last constraint in (1), which can be derived as a transversality condition, may be regarded as the requirement of fishery sustainability. In practice there will always be sporadic disturbances such that the steady state will serve as a target point around which the optimal policy will fluctuate rather than converge to.

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⁶ It may be pointed out that for biomass growth functions goodness of fit as measured by R^2 is generally very low.

⁷ For Denmark the R^2 statistic is necessarily zero as the regression is on a constant only.

⁸ Since there is only one explanatory variable the F statistic is incomputable. In the case of Iceland, which utilizes panel data the DW-statistic is meaningless.

⁹ The Danish cost function has been calibrated and hence there is no statistics

¹⁰ An alternative measure would be $(h_{acr}-h_{opt})/h_{opt}$. This, however, is complementary to ϕ in the sense that they add to one. Which one to use is therefore a matter of taste.

¹¹ We have chosen not to show the ϕ_t -diagrams as $\phi_t \rightarrow \infty$ whenever a harvest moratorium is optimal. These cases show up as missing points in the diagrams, rendering the diagrams uninformative.

¹² $\dot{H} = H_h \dot{h} + H_x \dot{x} + H_\lambda \dot{\lambda}$. From the necessary conditions, $H_h = 0$, $H_x = \delta\lambda - \dot{\lambda}$. Finally, by the construction of the Hamiltonian function, $H_\lambda = \dot{x}$