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On the rational utilization of the Icelandic cod stock

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The Icelandic cod stock is analysed with respect to the probable effects of different harvesting strategies on yield, spawning stock biomass, and economic benefits. Simulations are used to investigate the probability of stock recovery and collapse. Potential yield and economic benefits/costs are also investigated, using stochastic and deterministic models. In stochastic simulations, attention is paid to the apparent stock–recruitment relationship, the highly variable weight-at-age and maturity-at-age in Icelandic waters along with the inevitable inaccuracies in current and future assessments. Regardless of method, substantial reduction in catches from recent (1993) levels is seen to be necessary in order to rebuild the stock. In the deterministic model, profit maximization mandates closure of the fishery until the stock is rehabilitated. Using the stochastic model, it is predicted that recent catch levels lead to eventual extinction of the stock with high probability. A management procedure is formulated and its application to the model is shown to lead to stabilization of the stock around an economically and biologically acceptable level.

Key words: Beverton–Holt, economic models, Ricker, stochastic models, stock rebuilding.

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Introduction

This paper describes some of the work done under the auspices of a joint working group of the Marine Research Institute of Iceland (MRI) and the National Economic Institute of Iceland (NEI), where utilization of the cod stock was investigated with the aim of comparing alternative management strategies for achieving maximum yield over the long term[1].

The biological aspects were modelled using a cohort model (Beverton and Holt, 1993) with a recruitment function of the Beverton–Holt form. The economic aspects were modelled using an aggregated one sector model. There are two versions of the model, one deterministic, similar to the ones studied in Clark (1991) and Árnason (1980), and a stochastic one, where recruitment, weight, and maturity at age are all subject to random fluctuations[2].

The Icelandic cod stock has been severely depleted and is currently far below benchmarks such as the maximum sustainable yield level (Anon., 1992; Stefánsson, 1992). Therefore, not only are desirable long term management policies studied here, but also the dynamic problem of how to rehabilitate the stock.

In the deterministic version, management paths were calculated which optimize given economic criteria such as pure profits, net export revenues, or a particular utility function incorporating risk averse attitudes. The main result of these calculations was that when the objective is to maximize profits or contribution to net exports, it is optimal to cease fishing completely until the stock has reached optimum size. When aversion to fluctuations in income were taken into account it was found to be optimal to rehabilitate the stock more slowly, taking some catches every year.

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[1] Apart from the authors of this paper the members of the working group were Brynjolfur Bjarnason, Chairman, Jakob Jakobsson, Managing Director of the MRI, Kristjan Thorarinsson of the Federation of Icelandic Fishing Vessel Owners, and Thordur Fridjonsson, Managing Director of the NEI.

[2] Palsson *et al.* (1993) and Lane and Kaufman (1993) discuss various goals of stock management and compare different management rules using stochastic models similar to the one used here.

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In the stochastic version no attempt was made to optimize. Instead a management procedure, based on a piecewise linear total allowable catch (TAC) rule, was formulated which specified total allowable catches each year based on the estimated size of the spawning stock in the previous year. The TAC-rule was formulated such that, in stochastic equilibrium, the stock will fluctuate around a specified median size. The procedure has a maximum catch ("ceiling") and also a minimum catch ("floor"). Three values of the minimum catch, having direct relevance to current debate on TAC decisions, were considered. It was seen that if the minimum catch was too high, not only did profits suffer but there was a substantial probability of the stock collapsing in a few years if the rule was enforced regardless of the size of the stock. As expected, profits were maximized by the rule having the lowest floor. The utility calculations favored minimum catches in the range of 100 000–175 000 tonnes per year.

An analysis of the effects of some departures from the assumptions of the model was conducted, starting with an investigation of the effects of changing the recruitment function to Ricker form (Ricker, 1954). Then, allowance was made for stochastically varying coefficients in the recruitment function and, finally, the consequences of autocorrelated growth and maturity changes were investigated. The main conclusion from these analyses was that the effect of using the Ricker curve is considerable in terms of increasing collapse probabilities, but the other deviations from assumptions have less of an effect on the conclusions.

Finally, an attempt was made to evaluate the results of different management paths on overall economic aggregates, such as gross domestic product (GDP) and foreign debt. The macroeconomic model of the NEI was used for this purpose.

In the second and third sections, the biological and economic models, respectively, are described. Following this the various measures of efficiency used are discussed. In the fifth section the results of the stochastic simulations are presented. The sensitivity analysis follows. Implications for the national economy are presented in the section "Macroeconomic effects" and, finally, some conclusions are drawn.

A model of the cod stock

In the cohort model described by Beverton and Holt (1993) the fish stock is assumed to consist of a number of age groups. Here it is assumed that fish will enter the stock at age 3 and will reach the age of 14 at most. Thus, in this case, the model encompasses 12 age groups. The number of fish, a years of age, at the beginning of the year y is denoted by $N_{a,y}$. The number of fish in the cohort at the beginning of the next year is given by:

$$N_{a+1,y+1}=N_{a,y}\exp(-s_{a,y}F_y-M_{a,y}) \qquad 3\leq a\leq 13$$

where F_y is overall fishing mortality in year y (defined as the average over ages 5–10), $s_{a,y}$ is the fishing pattern or selectivity by age group, and $M_{a,y}$ is the natural mortality which here is assumed to be equal to 0.2 for all ages and years. Of course, $N_{15,y}=0$. The number of fish in the age group a caught during year y according to the Baranov equation (Baranov, 1918) is:

$$K_{a,y}= s_{a,y}F_y/(s_{a,y}F_y+M_{a,y})\times(1-\exp(-s_{a,y}F_y-M_{a,y}))N_{a,y}$$

and the catch in weight units during year y is

$$Q_y=\sum_{a=3}^{14} w_{a,y}K_{a,y},$$

where $w_{a,y}$ is the average weight of fish aged a in year y in the catch. The term "catchable stock" will be used to denote the total biomass of fish aged 4–14 at the beginning of year y:

$$\bar{B}_y=\sum_{a=3}^{14} v_{a,y}N_{a,y},$$

while the exploited biomass is defined as:

$$B_y=\sum_{a=3}^{14} v_{a,y}s_{a,y}N_{a,y},$$

where $v_{a,y}$ is the weight of fish of age a in year y in the sea. Here it has been assumed that $v_{a,y}=w_{a,y}$. The spawning stock during the spawning period is:

$$S_y=\sum_{a=3}^{14} u_{a,y}p_{a,y}N_{a,y}\exp(-s_{a,y}F_yf_a-M_{a,y}m_a)$$

where $u_{a,y}$ is the weight of fish of age a in year y during the spawning period, $p_{a,y}$ is the fraction of fish of reproductive capacity of age a in year y, f_a is the fraction of the total annual fishing mortality inflicted on age group a before spawning commences, and m_a is the fraction of the natural mortality inflicted on age group a before spawning.

The model is closed by assuming a recruitment function that relates the number of 3 year old fish at the beginning of the year to the size of the spawning stock three years earlier: $N_{3,y}=R(S_{y-3})$. Here, a Beverton–Holt functional form was used for R, *viz*:

$$R(S)=\alpha S/(1+S/k)$$

where α and k are positive constants. However, for 1993–1995, projected recruitment was based on available predictions (Anon., 1993a,c) which were: 137, 73, and 130 millions of fish in 1993, 1994, and 1995, respectively.

The long-term values of parameters, used in the deterministic simulations are presented in Table 1. The proportion mature, weight-at-age, and the selection pattern were averages of the estimated values for the years 1984–1993. The initial stock size, maturity, and weight-at-age were taken from Anon. (1993a). These values are given in Table 1.

Table 1. Input data for simulations. Starting values and long term values for proportion mature at age (p), weight at age (kg) in the catches, (w) and spawning stock (u), selection pattern (s), proportion of fishing mortality (f) and natural mortality (m) inflicted before spawning.

	Long term values of parameters						Stock size (N), maturity and weight-at-age in 1993			
Age	p	w	u	s	f	m	N	p	w	u
3	0.02	1.27	0.95	0.07	0.09	0.25	146.43	0.04	1.27	0.95
4	0.09	1.80	1.51	0.33	0.18	0.25	119.75	0.16	1.88	1.51
5	0.30	2.53	2.32	0.60	0.25	0.25	62.57	0.39	2.63	2.42
6	0.58	3.51	3.41	0.86	0.30	0.25	32.53	0.62	3.62	3.49
7	0.82	4.66	4.69	1.09	0.38	0.25	8.75	0.93	4.65	4.77
8	0.91	6.09	6.15	1.15	0.44	0.25	5.35	0.97	6.14	6.20
9	0.95	7.78	7.79	1.15	0.48	0.25	4.16	0.95	7.78	7.79
10	0.97	9.61	9.65	1.15	0.48	0.25	1.03	1.00	9.61	9.65
11	0.99	11.37	11.72	1.15	0.48	0.25	0.14	1.00	11.37	11.72
12	0.97	13.09	13.24	1.15	0.48	0.25	0.03	1.00	13.09	13.24
13	0.99	14.60	14.28	1.15	0.48	0.25	0.02	1.00	14.60	14.28
14	1.00	16.32	15.87	1.15	0.48	0.25	0.01	1.00	16.32	15.87

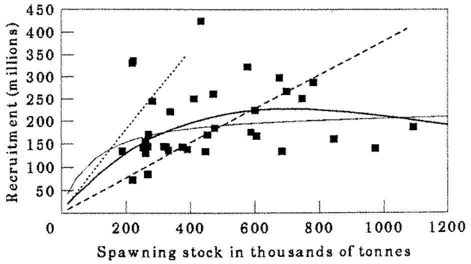

Figure 1. Icelandic cod stock and recruitment data (points) with fitted Beverton–Holt (B–H, thick curve) and Ricker (thin curve) stock–recruitment curves. Also shown are replacement lines corresponding to typical (dashed line) and unusually high production (dotted line).

The long-term parameter values in Table 1 were used from 1997. Values in 1993–1996 were interpolations of the long-term and initial values. The values of parameters in the recruitment function were α=2.5, k=98.4. The function gives a prediction of recruitment in terms of millions of individuals. Figure 1, taken from Anon. (1993c) shows the data and the fitted recruitment function along with replacement lines corresponding to typical and unusually high production (Sissenwine and Shepherd, 1987; Anon., 1993d).

In the stochastic simulations, several of the above quantities were taken to be random variables. An attempt was made to take account of measurement error in the stock size and variability in future recruitment as well as the proportion mature and weight-at-age.

The initial stock size was based on random perturbations from the estimates given in Anon. (1993c). The random perturbations were obtained by fixing an initial selection pattern in the terminal year and drawing the fish mortality from a log-normal distribution (with bias correction). The standard deviation of log (F) was taken to be 0.15. A VPA (Gulland, 1965) was run with these values and the selection pattern was recomputed based on earlier years. The VPA was rerun until the selection pattern was stable.

The above needs to be modified since there is more information (from groundfish surveys) on age groups 3–5 in the initial year than that contained only in the selection pattern. This information was incorporated by assuming the 3 year old cod in numbers to be estimated with a 20% standard error based on the groundfish survey and further assuming that the VPA-generated fishing mortality table was correct. Thus, the number of 3–5 year old fish in the beginning of 1993 was projected forward from the survey-based estimated number of the 3-group for each of these yearclasses.

The inevitable error in the spawning stock estimate for the previous year was taken into account by assuming that the estimated fishing mortality was unbiased but subject to a log-normal error with mean 1 and standard deviation 0.15. In other words, in year y the estimated fishing mortality is generated by

$$\hat{F}_y=F_y\exp(0.15X_y-0.15^2/2),$$

where $\{X_y\}$ are i.i.d. standard normal random variables. The selection pattern was assumed to be known and fixed. The selection pattern in 1992 was assumed to be equal to the average of the selection patterns in 1989 and

1990. Thus, after an overall true fishing mortality had been generated for 1992, iterative VPA runs were made to obtain this average selection pattern. The average pattern along with the overall fishing mortality yielded the "true" stock size. For future years, this same selection pattern was used for generating populations and catches. The pattern was assumed unknown to the management process, however, and thus had to be estimated for each future year. This was done by the same iterative method, based on the randomly perturbed $\hat{F}_y$. This choice of simulating the estimation error is one of several possibilities mentioned e.g. in Anon. (1993d) and Restrepo *et al.* (1990). The choice of the standard errors is along the lines indicated in Guðmundsson (1994).

To generate random fluctuations in recruitment, the recruitment function was multiplied by a log-normal random variable of the form $\exp(0.35X - 0.35^2)$, where X is standard normal. The recruitment estimates for 1993–1995 were multiplied by a log-normally distributed random variable with a 25% standard deviation.

As seen in Anon. (1993a,c) and Steinarsson and Stefánsson (1991), growth and maturity can be quite variable and this variability therefore needs to be included in the simulations. The proportion mature and weight-at-age in the biological model were obtained by selecting a year at random and assuming that the maturity at age and weight-at-age for a cohort will change additively in the same fashion next year as in the year selected. The changes in these values were assumed to be independent. If simulated maturity exceeded 1 it was truncated to 1.

A model of revenues and costs in cod fishing

To determine the optimal exploitation of fish stocks, one must incorporate a model for revenues and costs for different fishing policy alternatives. Such a model can be quite encompassing, such as the one on which the Nordic Fishery Management Model is based (Ólafsson *et al.*, 1992), or one can simplify and account for only the most important economic factors that affect decisions regarding an efficient fishing effort, as attempted here. Uncertainty in economic factors used to calculate revenues and costs in cod fishing was ignored.

Revenues and price elasticity

On the revenue side it was assumed that the (more or less processed) cod catch is sold at a certain unit price, making total revenues equal to the product of total weight of catch and unit price. Allocation of catch to freezing, salting, fresh fish, etc. was assumed to remain unchanged in relative terms from the allocation in 1992. The price equation was derived by positing a demand function with constant price elasticity, equating demand to supply and inverting[3]:

$$P_t = P_0\ ((T_0 + Q_t)/(T_0 + Q_0))^{-1/\varepsilon}$$

where: P_t = the price of cod products in year t in terms of (Icelandic krónur) ISK/kg of raw fish;
P_0 = the average price of cod products in 1992 which we have estimated at 110 ISK/kg on the basis of data on export by tariff numbers (Anon., 1993e) and the catch of cod in 1992;
Q_0 = 268 000, the cod catch in 1992;
Q_t is the cod catch in year t;
T_0 = the total supply of cod from other countries in traditional markets which we have set at 1 500 000 tonnes for the simulation period;
ε = the price elasticity of demand for cod which we have estimated to be 2 on the basis of data from FAO on world catch of cod and the price cod products from Iceland adjusted for inflation with the Consumer Price Index in the main markets. Ordinary linear least square estimates of log (real price of Icelandic cod products) on log (total catch of cod) and a constant on the basis of data for 1979–1992 gave an estimated elasticity of 2.05.

Iceland's market share for North Atlantic cod was approximately 15–20%, based on the 1992 cod catch (around 270 000 tonnes). If supply from other countries remains unchanged, as well as other factors that influence the supply and demand for cod products, a 100 000 tonnes reduction in the supply from Iceland causes the market price to increase by 3% according to these assumptions. Supply was taken to be independent of the price.

It was assumed that the price fishing operators receive is a fixed ratio (62%) of the final price based on estimates for 1992.

Costs

Catch per unit of fishing effort

The cost side for cod fishing is based on the intensity of fishing effort, i.e. how large effort needs to be, given the size of the catchable stock, to obtain a predetermined catch. Estimates of this relationship are available where the fishing effort is measured in terms of days fishing at sea (Helgason and Kenward, 1985). The estimate we use here is close to Helgason's and Kenward's estimate for trawl, but lower than some known estimates[4]. The effort index was determined as:

$$E_t = \lambda\ Q_t\ (B_0/B_t)^{\alpha}$$

where: B_t is the exploited biomass in year t;
B_0 = 438 000 is the exploited biomass in 1992. This was changed to the simulated value in each run for 1992 in the stochastic simulations;
α = 0.7 is the elasticity of fishing effort with respect to B_t;
λ = 1.52 is a scaling constant determined by the units in which fishing effort was measured.

Costs per unit of fishing effort

Total costs of fishing were taken to be proportional to the fishing effort: $C_t = c\ E_t$. Future productivity gains and possible efficiency gains due to changed fleet composition were not taken into consideration. The coefficient c was estimated to be 46.8 on the basis of data for 1992. It follows that costs for each vessel were fixed irrespective of how large the catch was. This ignores the share system in effect on Icelandic fishing boats, i.e. that the fishermen receive a certain percentage of the boats' revenues. Fishermen's 1992 wages were assumed to accurately reflect the social opportunity cost and in the calculations they were kept fixed at their 1992 level. If the share system will be retained unchanged and the cod stock recovers so that the catches increase, fishermen's wages will be far higher than assumed here with profits of fishing operators suffering to the same extent. However, the overall social benefits of building up the cod stock should not change.

Profits in fishing are therefore given by $\Pi_t = \gamma \cdot P_t \cdot Q_t - C_t$ where $\gamma = 0.618$ is the fraction of the price of processed fish that accrues to fishing operators.

Costs in fish processing

The cost of fish processing was taken to be proportional to the weight of raw material processed. This can be justified within the model by pointing out that therein high prices and limited supplies of fish go together as well as low prices and large supplies and it is likely that limited supplies will lead to increased unit costs and large supplies to lower unit costs in the fish processing.

Difference between market price, historic cost, and social costs

When making economic decisions the only costs that matter are avoidable costs. In cases of unemployment, the correct societal cost of labor lies somewhere between zero and the market price. Thus, calculations based on the assumption of zero societal costs should be regarded as an extreme value aimed at clarifying the implications of a significant difference between societal costs and market price.

In the model simulations three methods were used to calculate the costs in fishing operations. The first method (Method 1) prescribes that all costs be calculated at market prices. This method was used when revenues, costs and profits were calculated at equilibrium (see the following section).

The second method (Method 2) prescribes that all direct and indirect domestic costs associated with cod fishing and processing be set equal to zero. This is based on the assumption that no alternative uses can be found for the labor and capital tied up in the cod fisheries.

The third method (Method 3) was used in the deterministic simulations and was a compromise between the first two methods. This method prescribes that the costs of fixed capital used in the fishing operations be lowered by seven-eighths at the beginning of 1994, six-eighths in 1995 and so on until 2001 when all the fixed costs are included. Thus, it is assumed that there are no alternative uses to be found for vessels which catch cod at present nor that they can be sold out of the country. Furthermore, this situation was assumed to change over time so that from 2001 onwards it will be possible to adjust the size of the fishing fleet to the needs of cod fishing without making allowance for special costs.

The model does not take account of the possibility that when cod fishing decreases, important markets and skills can be lost which might prove costly to restore. Nor was any account taken of the possible costs of regional impacts which is an important issue in Iceland. The influence of these factors is to make it more desirable to approach the rebuilding of the cod stock in a gradual fashion.

Graphic solution to the maximization of profits

Since the stock–recruitment function was increasing and asymptotic, it was clear that increases in catches will eventually lead to declines in the spawning stock biomass. Similarly, if the spawning stock biomass is to reach very high levels, this can only be achieved within the model by reducing catches. Thus, the maximum steady-state catch is around 392 000 tonnes at a spawning stock of 1.1 million tonnes and an increase in effort beyond this point leads to a reduced steady-state catch (Fig. 2).

The spawning stock biomass has shown a clear declining trend for the past decades, from well over 1 million tonnes in the years after 1950, to 1993 levels of some 200 000 tonnes (Anon., 1993c). Although this does indicate the potential for the spawning stock to become quite large, it is likely that conditions in the ocean were more favorable before 1965 than they are now, e.g. in terms of temperature and zooplankton production

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[3] The ratio between relative changes in demand and relative price changes is called the price elasticity of demand. If the price elasticity of demand is 0.5, a 10% increase in supply will lead to a 20% decrease in the price, assuming that prices adjust to equate demand and supply.

[4] Danielsson (1994) estimates this elasticity to be around 1.

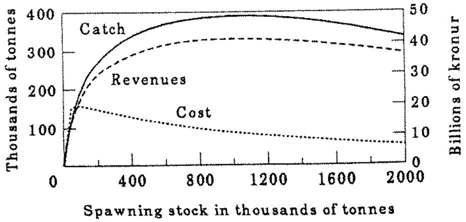

Figure 2. Equilibrium catches, revenues and costs against steady-state spawning stock.

(Anon., 1993a). Thus, one should interpret with care the results from the model when the spawning stock exceeds 1 million tonnes since density dependent factors may appear at such stock sizes e.g. in weight-at-age or recruitment. Some of the models used, however, indicate the economic desirability of maintaining the stock at such levels and this necessitates the use of a fairly wide range of stock sizes.

Figure 2 also shows steady-state revenues and costs (calculated by Method 1). When the gap between the revenue curve and the cost curve is largest – at a spawning stock of 1.7 million tonnes (a catchable stock of 2.7 million tonnes) – the corresponding steady-state spawning stock maximizes profits. This spawning stock gives a steady-state catch of 370 000 tonnes per year[5]. Under these steady-state conditions, profits from cod fishing amount to almost 16.7 billion krónur per year[6].

The spawning stock was estimated to be 209 000 tonnes in the spring of 1993 and the catchable stock 626 000 tonnes. As Figure 2 shows, under these conditions cod fishing suffers a slight loss as the revenue and cost curves intersect at a point where the spawning stock is 220 000 tonnes, giving a steady-state catch of 275 000 tonnes. Furthermore, under these conditions, the stock exhibits large fluctuations because fishing is based on few and young age groups. In this case, the probability of the collapse of the stock because of poor recruitment for a number of years in a row also becomes significant, as we shall see below.

It should be noted that there are strong indications that recruitment in recent years has been significantly lower than the Beverton–Holt recruitment function would entail and surveys of 0–2 groups indicate that it will remain so for the next few years. Under these circumstances, the catch that can be achieved without a decline in the stock is substantially lower than the steady-state catch.

Alternative objectives for fisheries management

Maximization of the present value of profits

In economic analysis it is most common to define maximization of profits as the desirable objective. The previous section discussed the steady-state catch and stock which maximizes annual profits. It is generally assumed that people place a greater value on present consumption and income and that this is reflected in positive interest rates. In this light, it is appropriate to base the analysis on the present value of the time series, Π_t, of profits

$$\sum_{t=0}^{\infty} \Pi_t/(1+r)^t,$$

where r>0 is the (real) social discount rate. It can be shown that the higher the interest rate – and thus the greater the desire for current income – the lower the efficient steady-state size of the cod stock and the steady state catch as well (e.g. Clark, 1991). In the extreme case of infinitely high interest rates the future is completely discounted and the entire emphasis is on increasing current income and consumption. Thus, high interest rates discourage a reduction in fishing to build up the cod stock. The benchmark discount rate used here was 5%, but in some cases, results are presented for r=10% and 15%. The two last values are very high for social discount rates.

Maximization of the present utility of consumption

People generally not only look at the present value of income on offer but also at how variable it is. It is usually assumed that people prefer a stable to a fluctuating income, *ceteris paribus*. It is possible to take this aversion to fluctuations into account by not using incomes or profits directly but instead measuring the utility of a given income (assumed to be equal to consumption) flow (I_t, $t \geq 0$) by:

$$\sum_{t=0}^{\infty} u(I_t)/(1+r)^t$$

where u is a concave utility function. This measure is particularly relevant in the stochastic simulations, where the expected utility of a given policy, given the probability distribution of the outcomes, is estimated by

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[5] Clearly, due to random fluctuations and measurement errors, the steady-state solution is not attainable as an absolute objective to be maintained from year to year. This will be discussed further in Section 5.

[6] For comparison, in 1992 GDP was 382 billion ISK and total exports were 124 billion ISK (Anon., 1993b).

taking the arithmetic average of simulated utility over a number of replications[7].

Econometric estimates indicate that private consumption in Iceland fluctuates in almost direct proportion to total export earnings (Daníelsson, 1991; Baldursson and Magnússon, 1993)[8]. The ratio between export earnings and disposable income is even more stable. Here it has been assumed that total consumption will be in direct proportion to total net export earnings. The value of imported inputs to cod fishing and processing in millions of krónur were assumed to be given by

$$M_t = m \cdot C_t + n \cdot Q_t$$

where m=0.4, the ratio of imported inputs in the cost of fishing operations (including that of support sectors); n=11.44, the value, in millions of krónur, of imported inputs in the costs of fish processing operations (including that of support sectors) per thousand tonnes of cod processed[9].

Net export earnings (or domestic value added) of cod fishing and processing are then given by $V_t = P_t \cdot Q_t - M_t$. Hence, we can assume the income flow, I_t, is proportional to $X^0 - M^0 + V_t$, where $X^0 - M^0$ are net export earnings of other export sectors (including that of other marine sectors) in the initial year 1992; this variable was estimated to be 45 billion krónur here.

A form commonly assumed for the instantaneous utility of consumption is the constant relative risk aversion form: $u(c)=(c^{1-\sigma}-1)/(1-\sigma)$, where c is consumption and $\sigma = -u''(c)c/u'(c)$, is the coefficient of relative risk aversion (see e.g. Lucas, 1987; Blanchard and Fisher, 1989; Varian, 1992). The function is scaled so that it changes to log(c) when $\sigma \rightarrow 1$. This is the form assumed here, with values of σ ranging from 0 to 6. Common values in econometric studies are in the vicinity of 2 (Lucas, 1987). When $\sigma=0$, $u(c)=c-1$ and maximization of the present value of utility is equivalent to maximization of the present currency value of consumption. In our model this is equivalent to maximizing net export earnings or domestic value added of cod fisheries.

Results of model simulations

The previous two sections described the models and assumptions used in this study whereas this section presents results of calculations and simulations, starting with optimal paths in the deterministic version of the model, and then going on to biological and economic results of simulations with the stochastic model, based on a certain family of catch control laws.

Deterministic calculations

Table 2 shows the paths for the period up to 2013 for annual catches which maximize the present value of profits (calculated by Method 3) for discount rates, r, of 5, 10, and 15%[10]. Also shown are paths based on the maximization of the utility function given above[11].

The maximization of the utility function was performed for values of the relative risk aversion, σ, in the range from 0 to 6 as indicated in the right panel in Table 2. When $\sigma=0$, this is equivalent to maximizing the net revenues of domestic agents from the export of cod products (or profits, with costs calculated by Method 2), because a proportional relationship between consumption and net export earnings is assumed. The discount rate was fixed at 5% in the utility calculations.

The bottom three lines in Table 2 show the present value of future profits for different discount rates. The cost of choosing each path is therefore the difference between the discounted profits this path yields and the discounted profits associated with the most efficient path. For example, assuming a 5% discount rate, it can be said that it costs 61=246–185 billion krónur to choose the path in the right-most column rather than the path in the left-most column. This is a cost which is incurred because it is not judged feasible to reduce fluctuations in consumption through foreign borrowing and because there are no alternative uses for the labor and capital tied in the fisheries during the period when the stock is built up. These figures must, of course, be interpreted with care and in light of the assumptions discussed above.

It is worthy of note that, without exception, these results indicate that it is beneficial to reduce the intensity of the fishing effort sharply over the next 2–3 years. However, high interest rates, a low social cost of labor

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[7] Under some assumptions on the preferences of people as regards different probability distributions of income ("lotteries", for short) it may be shown that there exists a utility function such that a set of lotteries may be preference ranked by the expected utility of each lottery. See Chapter 11 of Varian (1992) for an introduction to these issues.

[8] Marine products are approximately 50% of total exports, and cod has usually amounted to about half of marine exports (see Anon., 1993b).

[9] No estimates of these numbers for cod exist, but these numbers come from a model for the groundfish fishing and processing which is used for forecasting at the National Economic Institute, Reykjavik, Iceland. The details of this model have not been published.

[10] The maximization is done on an infinite horizon using the numerical optimization option of a spreadsheet program. Interested readers can get the technical details of these calculations from the authors.

[11] It is more illuminating in the deterministic context to interpret σ as the inverse, say $\gamma = 1/\sigma$, of the elasticity of substitution of consumption between two points in time, infinitesimally close. For high values of σ the elasticity becomes low – indicating a low willingness to substitute consumption now for later – and vice versa. See Chapter 2 of Blanchard and Fischer (1989).

Table 2. Optimal catch trajectories in the deterministic model. Catches in thousands of tonnes, maximising I. and II. Catches in 1992 and 1993 were predetermined.

	I. Present value of profits r (%)			II. Present value of consumption adjusted for aversion to fluctuations, discounted at r=5% p.a. σ			
Year	5	10	15	0	2	4	6
1992	268	268	268	268	268	268	268
1993	230	230	230	230	230	230	230
1994	0	0	0	0	55	108	134
1995	0	0	0	0	113	142	158
1996	0	0	0	91	157	171	181
1997	30	105	212	190	192	197	202
1998	158	205	237	251	222	221	222
1999	233	258	268	285	248	241	239
2000	280	293	290	312	271	260	255
2001	319	318	309	332	291	277	269
2002	336	341	336	349	308	291	282
2003	345	353	353	359	324	304	294
2004	350	358	362	366	338	316	304
2005	354	366	370	373	349	326	314
2006	363	377	379	381	359	335	322
2007	368	383	387	386	366	343	330
2008	383	386	389	389	371	349	337
2009	383	389	390	391	376	355	343
2010	383	391	391	391	379	359	348
2011	383	391	392	392	381	363	352
2012	383	391	392	391	383	366	356
2013	383	392	392	391	385	378	360
Present value of profits in billions of kronur:							
5%	246	244	238	225	210	198	185
10%	96	97	96	93	84	76	68
15%	51	53	53	52	47	41	36

and capital because of few alternative uses in both the short and long term, aversion to fluctuations in income as there are difficulties in smoothing consumption through borrowing during contractionary periods, are factors that support a slower rehabilitation of the cod stock than would be efficient if the sole objective was to maximize the discounted value of profits[12].

Stochastic simulations

The calculations above did not take account of uncertainty, which is included in the simulations described below, where an attempt was made at modelling the inherent randomness of the biological system. Certain management procedures, i.e. formulas for the determination of the total allowable catch, were tested using the simulation model described in the second section. Extrapolations were made for 25 years into the future and 100 paths were simulated in each case. The procedures were selected *ad hoc* and represent only a few of an infinite number of possibilities.

A good management procedure should lead to a biologically and economically desirable long-term equilibrium (i.e. stochastic steady state distribution). The rule should even out fluctuations in catches as much as possible and the procedure should minimize the probability of a collapse in the stock. Clearly, these goals are not attainable simultaneously. For example, an attempt to eliminate interannual fluctuations in catches by holding TACs constant independent of stock size may lead to the eventual extinction of the stock, as seen below.

Simplicity of the procedure is important for various managerial and political reasons. Rules based on fishing mortalities are, in this respect, considerably inferior to rules directly relating catches to quantities such as spawning stock biomass or exploitable biomass. Another aspect relates to the comparison of the management procedure to a method which is already in place. For a large number of stocks there is no formal management objective. However, there is usually some *de facto* form of management and, in some cases, the current method of managing the stock can be put into a parametric framework. In such instances it may be feasible to formulate alternate strategies in terms of parametric deviations from the current setting. For example, a common claim is that "catches must not drop below x tonnes". In this situation it is interesting to compare various management procedures which explicitly try to attain a certain minimum catch, even when the stock size is very low.

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[12] The cost of low market connections and skills is one more factor which would move the results in this direction were it included in the calculation.

The form of the management procedure used here is the following:

$$Q_y = \min(\max(Q_{\min,y}, \min(Q_{\max,y}, a(\hat{S}_{y-1} - b))), Q_{1.5,y})$$

where

$$Q_{\min,y} = \max(q_{\min}, (1-\delta)Q_{y-1})$$

$$Q_{\max,y} = \min(q_{\max}, (1+\delta)Q_{y-1})$$

and $Q_{1.5,y}$ is the catch obtained by setting the true F in year y to 1.5.

Thus, the procedure can be described as follows: First, a fixed fraction, a, of the estimated spawning stock in excess of a certain limit, b, is calculated. In these calculations, a=45% and b=50 000 tonnes. Then the total catch is lowered to a certain limit ("roof") if a higher value than this upper limit was obtained in the first step, but raised to a "floor", if a lower value than this lower limit was obtained. The roof is the smaller number of $q_{\max}$=450 000 and the catch in the previous year increased by the fraction δ=25%. The floor is the larger value of $q_{\min}$ and the catch in the previous year lowered by the fraction δ. Finally, the condition that the fishing mortality rate not exceed 1.5 was imposed. The value of 1.5 is a somewhat arbitrary choice, but this value needs to reflect an estimate of the maximum fishing mortality which the fleet can exert on the stock. Three minimum tonnage figures were tested: 125, 175, and 225 thousand tonnes.

The above class of rules was selected *ad hoc*. Still, it has enough flexibility such that, by varying its parameters, a wide range of characteristics can be attained and, in principle, the public and/or its representatives can select a rule out of this class which is satisfactory. This is not very theoretically satisfying, but may be no worse than positing a utility function for the public, subsequently to be maximized[13].

The management procedure above is a "constant catch" rule over a wide range of stock size. Hannesson and Steinshamn (1991) and Steinshamn (1993) investigate the relative merits of constant catch versus constant effort management rules. The former paper only considers a deterministic sinusoidal recruitment time path and finds, quite naturally, given that assumption, little difference in practice between the two methods. Steinshamn (1993) finds that in a stylized model of the north-east Arctic cod, with a Beverton–Holt recruitment function multiplied by a random error term, constant catch rules lead to extinction of the stock with high probability if recruitment is sufficiently variable. As we shall see this is also a feature of the rule considered here.

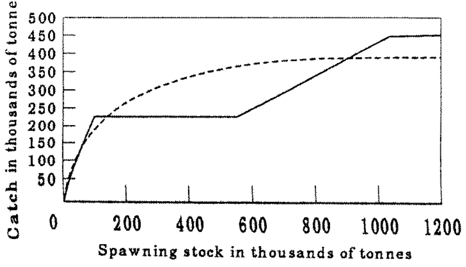

Figure 3. Steady-state catch (dashed curve) and management procedure (piecewise linear).

Figure 3 shows the management procedure as a function of the estimated spawning stock, assuming a minimum catch of 225 000 tonnes. At a spawning stock of about 90 000 tonnes, the restriction that F≤1.5 becomes binding. This is of course dependent on the cohort structure of the stock at each time, but, in Figure 3, the F=1.5 line segment of the management procedure is found by first selecting an F that pushes the stock into a certain steady state and then calculating (disequilibrium) catches corresponding to F=1.5. Limitations on changes between years are not taken into account in Figure 3.

Figure 3 gives the approximate dynamics of the deterministic model. The dynamics of the stochastic model are much more complicated and will not be investigated here except by simulation. The management procedure crosses the steady-state catch curve in four places. The origin is the first intersection and corresponds to extinction of the stock. The deterministic model requires an F of approximately 2.5 to push the stock to this equilibrium of complete collapse. The next crossing point is at a spawning stock of 38 000 tonnes and a catch of 105 000 tonnes, where F=1.5. In the deterministic model this is a stable equilibrium. The third crossing is at a spawning stock of 135 000 tonnes and a catch of 225 000 tonnes. This is an unstable equilibrium in the deterministic model, as only minor changes are needed in the spawning stock for it eventually to move upwards to the fourth equilibrium point of a spawning stock of 900 000 tonnes and a catch of 390 000 tonnes, or for it to move down towards the second equilibrium of F=1.5. The fourth equilibrium,

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[13] Solving the stochastic optimization problem corresponding to the deterministic one considered in the section on deterministic calculations is in any case a formidable undertaking since the related state space will be huge.

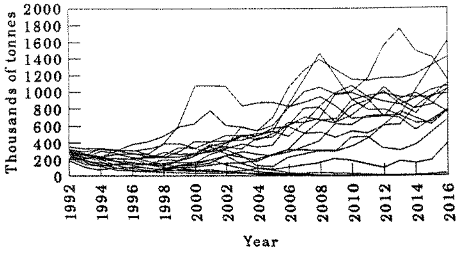

Figure 4. Spawning stock: 25 trajectories from simulation runs based on a minimum catch of 225 000 tonnes.

on the other hand, is stable: even if the spawning stock changes slightly, the management procedure moves it back into equilibrium. These dynamics are valid in the deterministic model but, as we shall see, a complete collapse can occur in the stochastic model, even if F is restricted to 1.5, in contradistinction to the former case.

The management procedure was determined so that it would yield an equilibrium spawning stock of 900 000 tonnes. This stock is somewhat smaller and the fishing effort more intense than indicated by the profit maximization calculations in the section on modelling revenues and costs. However, this size of spawning stock was chosen from the viewpoint that the Beverton–Holt model may not apply when the spawning stock exceeds 1 million tonnes and the catchable stock exceeds 2 million tonnes. When the stock has reached this size, density and multi-species effects may begin to arise. Not enough is known about these factors for it to be possible to place a value on their likely cost. Thus, it was decided to pre-select an equilibrium spawning stock which would be acceptable from both an economic and a biological standpoint. Figure 2 shows clearly that this is the case for a spawning stock between 900 000 and 1 million tonnes.

Figure 4 shows 25 of the 100 simulated paths for the spawning stock. The management procedure used was based on a minimum catch of 225 000 tonnes per year. As can be seen from Figure 4, in most cases the stock recovers, but in about a third of the cases it collapses.

Figure 5 gives results for the management procedure when $q_{\min}=175\,000$. The figure shows several bold lines which denote percentiles for the spawning stock each year, specifically the probability is 5%, 25%, 50%, 75%, and 95% of the spawning stock biomass being below the corresponding line in a given year. To show fluctuations from year to year the figure also shows five time paths from the simulations. The median size of the spawning stock will be around 500 000 tonnes in 2001 and the stock eventually stabilizes at just under 1 million tonnes. The stock recovers in 97 of 100 replications. The same largely applies with $q_{\min}=125\,000$, which leads to rehabilitation of the stock in all cases but it takes the medium stock size about two years less to reach 500 000 tonnes than under the 175 000 tonnes rule. The probability of collapse is crucially dependent on the postulated relationship between recruitment and the size of the spawning stock after 1996 as seen below. The picture changes dramatically when a minimum catch of 225 000 tonnes is maintained. Although the median size of the stock eventually reaches 600–800 000 tonnes, the stock collapses in over 30% of the cases.

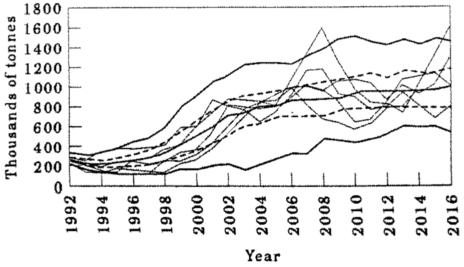

Figure 5. Spawning stock development corresponding to a minimum catch of 175 000 tonnes based on 100 simulations. Top and bottom, bold, solid curves: 5% and 95% percentiles in each year, respectively. Central, bold, solid curve: median for each year. Dashed curves: 25% (below) and 75% (above) percentiles. Thin lines: sample simulated trajectories.

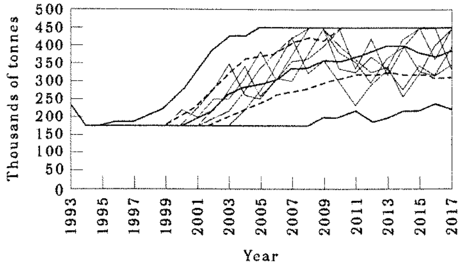

Figure 6. Catch development corresponding to a minimum catch of 175 000 tonnes based on 100 simulations. Top and bottom, bold, solid curves: 5% and 95% percentiles in each year, respectively. Central, bold, solid curve: median for each year. Dashed curves: 25% (below) and 75% percentiles (above). Thin lines: sample simulated trajectories.

Figure 6 shows the development of catches when $q_{\min}=175\,000$. The catch reaches 250 000 tonnes in 50% of the cases by 2003. With $q_{\min}=125\,000$ this takes about 2 years less time. With $q_{\min}=225\,000$ catches exceed 250 000 tonnes in 50% of the cases by 2010. In a third of the cases, the catch collapses along with the stock. In addition, the cost of reaching the minimum catch rises as the stock shrinks, making fishing operations highly uneconomical.

The main drawback to the management procedure appears to be that it allows considerable fluctuations in catches. The average absolute value of changes in the catch between years once equilibrium has been reached is about 40 000 tonnes, or about 12% of the average TAC. However, it is clear that there is a trade-off between the stability of the stock and the stability of the catch and, with the looming danger of a total collapse in mind, it is important to consider whether fluctuations in income can be smoothed by other means[14]. The main point to be made at this stage is that through sensible decisions regarding quotas it is possible to maintain a relatively stable stock with good yields. Determining the optimal rule must await further studies and it is clear that considerable research still needs to be done in this area.

Economic results

The economic model described earlier was used to calculate revenues and costs (calculated by Method 1) arising from the simulation paths discussed above. It is reiterated that the costs discussed here are societal and the share arrangement between fishermen and fishing operators is ignored. Table 3 shows the distribution of the present value of revenues, costs, and societal benefits from fishing and fish processing for the three cases discussed above. For example, the table shows that the present value difference in revenues between the 125 000 tonnes and 225 000 tonnes alternatives is 84 billion krónur. The cost difference is larger, or 128 billion krónur, and the profit difference larger still, or 215 billion krónur. The difference in terms of variability is also large, with the standard deviation of profits around 31 billion krónur if the 125 000 tonnes alternative is chosen but 195 billion krónur under the 225 000 tonnes alternative. These figures are, of course, exaggerated as, in the simulations, it was assumed that fisheries operations continue long after they would have been abandoned in reality as they would have become uneconomical[15].

Table 3. Distribution of revenues, societal costs and profits from cod fishing. Present value in billions of krónur using a 5% discount rate.

Minimum catch	Cumulative probability (%)	Revenues	Costs	Profits
125 000 tonnes	5	345	171	166
	25	377	158	193
	50	396	174	216
	75	417	192	243
	95	444	235	265
Average		395	179	217
Standard deviation		32	31	31
175 000 tonnes	5	305	159	132
	25	368	176	174
	50	392	192	194
	75	410	211	220
	95	447	259	243
Average		385	201	184
Standard deviation		49	46	77
225 000 tonnes	5	139	205	− 309
	25	194	233	− 225
	50	345	258	110
	75	394	398	156
	95	439	491	202
Average		309	307	2
Standard deviation		105	101	195

Average profits under the 175 000 tonnes alternative are about 33 billion krónur lower in present value terms than under the 125 000 tonnes alternative and considerably more variable with the standard deviation at 77 billion krónur. Under the 225 000 tonnes alternative the probability of incurring losses of more than 225 billion krónur is 25% while the probability of profits over 166 billion krónur under the 125 000 tonnes alternative and over 132 billion krónur under the 175 000 tonnes alternative is 95%.

It is clear that, according to these calculations, the 125 000 tonnes alternative is the best one in that it not only generates the highest but also the most stable profits. However, the 175 000 tonnes alternative also generates substantial profits so that its selection can perhaps be justified when additional considerations are taken into account.

As discussed in the section on alternative objectives, it may be more appropriate to use some measure of utility rather than profits. It is interesting to examine whether this changes the results in any way. As in the results of model simulations, it was assumed that consumption fluctuates in direct proportion to the purchasing power of net export earnings. This measure was calculated using a number of different values for risk aversion (0–6) and discount rates (5–15%). Perhaps the most appropriate value for the relative risk aversion coefficient is between 2 and 4 and for the discount rate, 5%. The utility was computed for a range of minimum catch levels. For very low initial catch levels, it becomes impossible to increase the catches fast enough if there is a restriction on the catch increase from one year to the

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[14] Attempts have been made in Iceland to force companies to smooth income fluctuations due to price changes. In principle there is no reason to exclude catch fluctuations from such schemes. However, it has proved difficult to reach political consensus on them.

[15] At least in Iceland they would, as there is no other sector which could finance subsidies that would make these fisheries economical for the vessel owners.

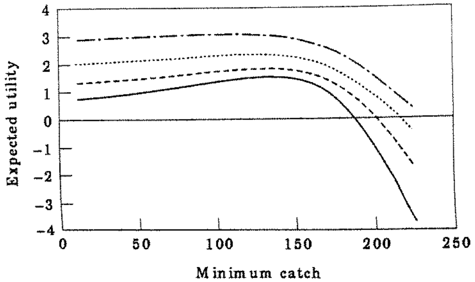

Figure 7. Simulated expected utility against minimum catch for interest rate, r=5% and coefficient of relative risk aversion σ=0 (–·–·–), 2 (· · · ·), 4 (– – –), 6 (——).

next. For the purpose of this analysis, therefore, this restriction was lifted for the first 5 years. Figure 7 gives the results for different risk aversion values and a 5% discount rate.

It is seen that, regardless of the risk aversion, the utility function strongly favors minimum catch values well below 200 000 tonnes and higher aversion favors higher minimum catch values, although the "best" minimum catch never exceeds 130 000 tonnes. However, the utility functions tend to be quite flat for most of the range between 100 and 200 000 tonnes. Qualitatively similar results are obtained with higher interest rates, but the peak of the utility function shifts slightly to the right, with the highest optimum floor reaching 160 000 tonnes at r=0.15 and σ in the range 2–6.

Further developments of the biological model

The biological simulation model described in the previous sections leaves out several sources of variation, and, clearly, the model also includes several assumptions. It is of interest to consider the effect of changing some of these assumptions or including some of the missing sources of variation. This section considers these issues. Only the 175 000 tonnes minimum catch option is considered, since the results seem fairly clear for 125 000 and 225 000 tonnes, and it is therefore unlikely that minor model or parameter changes will change those results to a major extent.

The stock–recruitment function

There is considerable uncertainty in the stock–recruitment relationship. In particular, it is not possible, based on the data, to discern between the Beverton–Holt and Ricker models. Further, given a particular model, the uncertainty in parameter estimates also needs to be reflected in the predictions.

The base stock–recruitment model used in this paper is the Beverton–Holt model, as obtained by fitting to the stock–recruitment data in Anon. (1993c). The model does not fit the data particularly well, and in fact the predicted recruitment at low stock sizes is considerably higher than has been observed in recent years. Further, as seen in Figure 1, at high stock sizes, the predicted recruitment from this curve tends to be above the observed recruitment.

The straight lines in the figure indicate the SSB obtained from a given level of recruitment. Based on these curves, it was noted in Anon. (1993c) that a fishing mortality of just under 0.9 will drive the stock size to zero in the Ricker model, whereas an equilibrium is attainable under the Beverton–Holt stock–recruitment model.

It is therefore of interest to compare results with those obtained from the alternative stock–recruitment function. The basic result is that, whereas the collapse probability is only 3% under the Beverton–Holt model, it rises to 8% when the Ricker model is used. Similarly, the coefficient of variation (CV) of the SSB in the year 2000 rises from 57% to 71%. The effect of the change in the stock–recruitment function is thus more than a trivial one. This finding is not surprising given that the model is recruitment-driven to a large extent.

Uncertainty in the stock–recruitment model

The parameters of the Ricker (or Beverton–Holt) recruitment model are estimated with considerable uncertainty. An estimate of the uncertainty can be obtained by the use of linear or nonlinear estimation techniques. Thus, a regression of ln(R/S) on S will not only give parameter estimates, but also their standard errors and correlation. These can be used to obtain the variance-covariance matrix of α and K. Almost identical results are obtained by using nonlinear minimization. In order to simulate the uncertainty in these parameters, they are simply assumed to come from a bivariate Gaussian density.

Thus, a stock–recruitment function is generated by drawing the two correlated parameters of the Ricker curve at random at the beginning of each simulation. The generated values are kept throughout one simulated time period. Similarly, the parameters of the Beverton–Holt curve can be drawn at random from a multivariate distribution. However, the standard errors of the Beverton–Holt parameters are large enough to make it possible for the randomly generated parameters to become negative and hence these parameters are drawn on log-scale.

The results indicate that the collapse probability for the Beverton–Holt model changes from 3% to 25% by going from the fixed parameter scenario to the random parameter scenario. However, the collapse

probability for the Ricker model only changes from 8% to 12%.

It is thus seen that the base Beverton–Holt model generates too many recruits at low stock sizes and simply allowing for measurement errors in the parameters of that model increases the collapse probability considerably. Although adding the measurement error to the Ricker model also increases the collapse probability, the effect is not nearly as severe, since the base Ricker curve already predicts low recruitment at current stock sizes. A further interpretation of these somewhat conflicting results is that the Beverton–Holt model is very poorly determined and probably too rigid for the data set at hand. Hence, although there was evidence of reduced recruitment at current (low) stock levels, this was not reflected in the parameters, which should have low enough standard errors to ensure that most of the generated curves are roughly linear from the current group of points down to the origin (0,0). The high standard errors will result in curves which can have slopes at the origin in a very wide range and this is in some contrast with the data. As a result of this, the two collapse probabilities from the Beverton–Holt model are probably exaggerations and the two from the Ricker model would seem closer to the truth.

Autocorrelated growth

The changes in proportion mature and weight at age are known to be quite important in this area (Steinarsson and Stefánsson, 1991; Anon., 1993c) and could be either positively or negatively autocorrelated. While the food supply might be expected to stay high for more than one year, and thus give a positive correlation in growth, fish are known to recover from starvation and regain their average weight fairly quickly implying a negative autocorrelation. The data on weight and proportion mature at age in Anon. (1993c) indicate a slight negative time correlation in the weight increase for most age classes.

The following *ad hoc* approach was used to simulate the effect of autocorrelation in maturity and weight changes. If T is the current year in the simulation, and Δ_T is the increment from the previous year, then next year's value is set to $x+\xi\Delta_T+(1-\xi)\Delta_t$ i.e. the weight/maturity increment is set to a weighted average of an increment selected at random from historical data (Δ_t from year t) and the increment in the previous year. This model will generate a serially correlated process with an autocorrelation of $\xi/\sqrt{\xi^2+(1-\xi)^2}$.

The effect of the autocorrelation is tested by using $\xi=0.25$, in the weight and maturity tables, corresponding to a serial correlation of about 0.32.

Using the Ricker stock–recruitment model with random parameters as a baseline, the collapse probability decreases from 12% to 11% as the autocorrelation varies from −0.32 to +0.32. For the same levels of autocorrelation, the CV of the SSB in the year 2000 decreases from 66% to 62%. Thus, the effect was relatively minor, at least in terms of these measures.

Macroeconomic effects

Cod products account for 40–50% of all merchandise exports from Iceland. Macroeconomic effects of large changes in cod catches are therefore expected to be substantial. The aim of this section is to indicate the likely effects of the implementation of the management procedures considered in the section on stochastic simulations. The projections were done in the deterministic biological model.

The minimum catch maintained was either 125, 175, or 225 000 tonnes. In addition, three variations on each main alternative were examined: a middle case, a high case, and a low case. In the middle cases it was assumed that recruitment would follow the projections of the MRI for 1992–1995 and model results used for recruitment from 1996 onwards. In the low cases it was assumed that recruitment during the period 1992–2001 would be 23% below forecasts. In the high cases it was assumed that recruitment would exceed forecasts by 31% during this 10 year period. These correspond roughly to the 25, 50 and 75% limits in Figures 5 and 6. The development of catches is shown in Table 4. It should be pointed out that the management procedure is based on estimates of the spawning stock during the spring of the previous year. Thus, the stock size during spring of 2006 would be used to determine the total allowable catch in 2007. Under the 225 000 tonnes alternative, the allowable catch in 2007 in the high case would be 275 000 tonnes.

The economic effects of each alternative were evaluated by holding the catch of other species than cod fixed from 1994 and estimating the impact of different cod catches and fishing costs on export production, imports, and the terms of trade. Most other assumptions, such as the volume of merchandise exports other than marine exports, public expenditures, exchange rates and foreign interest rates were the same in all cases. The only exception was that direct household taxes were adjusted over the simulation period (1994–2005) so that foreign debt as a percentage of GDP was about the same at the end of the simulation period in all cases. This was done to make the cases as comparable as possible. This method is of course biased against the 125/175 000 tonnes schemes, since it is evident that the ability to pay off the debt was greater, sometimes by a large amount, in these schemes than in the scheme of a 225 000 tonnes minimum catch. The NEI's macro-economic model was used to generate results based on these assumptions[16].

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[16] The model is described in Baldursson (1990).

Table 4. Development of catches for alternative minimum catches (125, 175 and 225 thousand tonnes) and different developments in recruitment (expected from stock-recruitment curve, expected, +31% and expected, −23%).

Year	Middle case			High case			Low case		
1994	125	175	225	125	175	225	125	175	225
1995	125	175	225	125	175	225	125	175	225
1996	125	175	225	125	175	225	125	175	225
1997	126	175	225	133	175	225	125	175	225
1998	158	175	225	166	175	225	147	175	225
1999	197	175	225	208	175	225	184	175	225
2000	246	175	225	259	181	225	227	175	225
2001	296	192	225	324	227	225	266	175	222
2002	328	240	225	369	283	225	294	198	194
2003	347	287	225	391	354	225	312	240	188
2004	360	320	225	402	389	225	325	277	189
2005	367	340	225	402	398	225	336	306	187
Stocks in the spring of 2006 in thousands of tonnes									
Spawning stock	891	854	341	892	910	663	861	825	65
Catchable stock	1797	1725	909	1838	1820	1406	1749	1676	335

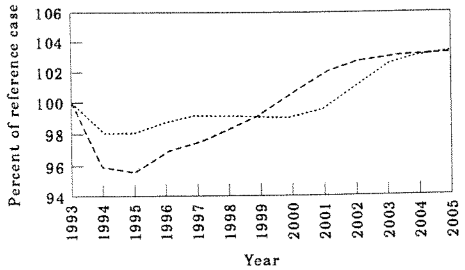

Figure 8. Gross domestic product for minimum catch = 125 000 and 175 000 tonnes based on expected recruitment. The case of minimum catch = 225 000 tonnes is set to 100. (· · · ·) 125 000 tonnes; (– – –) 175 000 tonnes.

Results were calculated as deviations from a reference case, which was chosen as the central case with a minimum catch of 225 000 tonnes. This is not advice that this is a desirable alternative. It is only used as a benchmark, reflecting catches in 1993.

The form of the results was in most cases similar (Fig. 8 illustrates the central case). GDP fell under the 125 and 175 000 tonnes alternative compared with the reference case although the effects were softened through foreign borrowing. Around, or before, the turn of the century a reversal of the results occurred with GDP in the lower minimum catch alternatives exceeding that in the reference case. These alternatives then maintained a 3% advantage over the reference case. The low cases represented a departure from the general results above. Under the lower minimum catch alternatives, GDP grew steadily following a contraction in the first two years while, under the low case, variation on the 225 000 tonnes alternative GDP contracted steadily. The GDP difference between the lower minimum catch alternatives and the reference alternative reached about 5% at the end of the projection period. In addition, there were large differences in stock size. If "green" GDP (i.e. GDP adjusted for changes in the value of natural resources) would be used instead of the traditional definition, the results would change in favor of the 125/175 000 tonnes schemes, especially in the "low" case.

Even if foreign debt at the end of the projection period was the same in all cases it rose in the first three years in the 175 000 case and more so in the 125 000 case. In the 125 000 tonnes scheme it was around 8% of GDP over the benchmark in 1996 in all cases[17].

Conclusion

An account has been given of attempts to estimate the optimal exploitation of the Icelandic cod stock. Although different methods and measures give different numerical answers, the point that stands out is that, from an economic standpoint, it is desirable to enable the spawning stock to grow in size at least three- to four-fold. This is also consistent with the biological view, although there the goals are somewhat different and the acceptable stock size somewhat lower. Subsequently, by reducing or increasing the catch with reference to changes in the stock, the stock can be maintained within desirable limits.

However, the most difficult part of the problem is to determine how to build up a stock that has shrunk to a very precarious economical and biological level. From a pure profit maximizing standpoint the answer is very simple. Fishing should be ceased until the stock has reached an acceptable size. The reason is also simple. Return on fish in the sea, at current stock sizes, is much higher than market rates of interest.

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[17] Net foreign debt was approximately 50% of GDP at the beginning of 1993 (Anon., 1993b).

However, this alternative is beset with economic and political problems which are difficult to quantify, although an attempt was made to do so above. Thus, it seems likely that the right approach is to catch some cod each year while making sure there is an overwhelming probability of the stock size increasing. Above, it was shown that a catch below 125 000 tonnes per year satisfies this condition. This is an alternative that is very likely to let the cod stock grow and yield high profits in a few years. If the catch is 175 000 tonnes, the overall results will be similar in most cases. A drawback to this alternative is that the stock is likely to decline further over the next few years so that the results become very sensitive to the causal relationship between the spawning stock and recruitment.

Furthermore, it was argued that at a constant catch of around 225 000 tonnes per year, similar to the catch in 1993, there is a significant probability that the stock will collapse. This alternative is also more costly in terms of effort and on average no profits will be earned. In sum, both from an economic and a biological standpoint, it must be recommended that catches should be reduced sharply from the current level, preferably to a level below 175 000 tonnes.

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Stock assessment and biological knowledge: can prediction uncertainty be reduced?

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The paper addresses whether we fully utilise our increasing biological knowledge in fish stock assessments. For illustrative purposes, repeated references are made to the assessment of the north-east Arctic cod stock. In many cases, existing knowledge may allow us to establish relationships for predicting short or medium term changes in vital population parameters determining mortality, growth, and recruitment. Ancillary variables in such relationships, with *a priori* justification for being chosen, could be parameters describing the state of the fish stock in question or the state of its biological or physical environment. Long time-series of biological data exist for several stocks, and these data series should be used for testing proposed relationships. Explanatory theories should be used for making predictions not dependent on the assumption that historical patterns will be repeated, increasing the empirical or informative content of our assessments.

Key words: stock assessments, biological knowledge, predictions, explanatory theories, empirical content, predictions, north-east Arctic cod.

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Introduction

The main problem dealt with in this paper is the question as to whether we are fully recognising and utilising our increasing biological knowledge in standard stock assessment procedures. The problem can generally be formulated by the two questions: when specifying our population models and assigning values to their biological parameters, do we make the best use of biological knowledge for predicting, with incorporated estimates of uncertainty, what will happen in coming years? What kind of knowledge is required for accurate and precise predictions and to what extent does it exist or can it be gained?

Surplus production in a fish stock is determined by its natural mortality, growth, and recruitment parameters. Natural mortality is seldom known or estimated but assumed constant at an agreed level from year to year. Growth can be continuously observed, but when projecting stock size and catches, assumptions have to be made about its magnitude. Recruitment can also be observed and estimated at the time it occurs, although usually with larger errors than for growth. For long-lived species, assumptions of strength of year classes not yet observed in the fishery are usually not of critical importance for short-term projections. However, for medium and long-term projections, assumptions on recruitment functions are usually the most critical part of the assessment. For short-lived species they are also critical for short-term projections.

How critical the assumptions are about the value of these biological parameters can be studied by sensitivity analysis, and such analysis should be done more often. However, sensitivity analysis does not solve the problem of assessing prediction errors; it shows only what parameters are most critical. For realistic assessments of prediction uncertainty, knowledge about the reliability of estimates of biological parameters, and their variations and causes of such variations, is required.

The ICES Working Group on Methods of Fish Stock Assessment (Anon., 1993a) discusses the different types of uncertainties to be considered and notes that, at present, few analyses include all sources of uncertainty. In many cases, only measurement error or recruitment uncertainty are dealt with, but this should be regarded as an important step forward and should be encouraged rather than criticised for being incomplete.

Comparatively little effort has been devoted to reduce stock prediction uncertainty and bias. It should especially be investigated whether information on

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