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Utilization of the Icelandic Cod Stock in a Multispecies Context

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Abstract *The purpose of this paper is to discuss rules for deciding Total Allowable Catch (TAC) for Icelandic cod. For this purpose, a bioeconomic model describing harvesting and processing of cod, capelin, and shrimp in the Icelandic marine ecosystem is constructed and estimated. The model is used to analyze the probable effects of harvesting strategies on biomass, catch, and economic benefits from the exploitation of these species. Simulations are used to investigate probability profiles of biological and economic variables, taking into account inaccuracies in assessments and uncertainties in predictions. Optimal harvesting strategies are also investigated using a deterministic version of the model and taking into account problems of unemployment, overcapacity, and aversion to fluctuations in consumption. The analysis shows that it is beneficial to reduce fishing from the cod stock in order to allow the stock to recover to its optimum size. This increase in the cod stock will result in big decreases in the catch of capelin and shrimp.*

Key words Bioeconomic model, fisheries management, Icelandic cod stock, multispecies models, risk analysis, simulations, TAC rules.

Introduction

In 1992, the Icelandic Minister of Fisheries asked the Marine Research Institute (MRI) to "prepare proposals for how individual fish stocks should be exploited with the aim of achieving the maximum yield over the long term from Icelandic waters." For this purpose a joint working group of the MRI and the National Economic Insti-

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tute (NEI) was established in January 1993.[1] The working group sent its final report to the Minister of Fisheries in May 1994 advocating a Total Allowable Catch (TAC) rule for cod. In spring 1995 the government adopted a formal TAC rule for cod. The rule dictates that annual TAC should be 25% of the fishable biomass (*i.e.*, 4 years and older), but not less than 155,000 tons.

This paper presents some of the analysis done for the working group. It is an extension of Baldursson, Danielsson, and Stefansson (1996), which considered the exploitation of the cod stock within a single-species model, to a model where several multispecies concerns have been addressed. Both papers show that it is extremely profitable to rebuild the cod stock to an optimum level. This optimum level is somewhat smaller in our paper's model, but the primary differences do not concern cod, but rather capelin and shrimp. It is shown that if the cod stock approaches its optimum level, then it will be necessary to decrease catch of shrimp and capelin by more than 50%. The new model predicts that decreases in the catch of shrimp will be greatest during the recovery of the cod stock, but that it will be possible to increase the catch of shrimp again when the cod stock approaches its optimum level.

The biological models for cod, shrimp, and capelin are discussed first, then formal rules for determining the exploitation of the three stocks are presented. Simple economic models are constructed to make it possible to discriminate between management strategies on economic grounds. The optimal harvesting paths are derived from deterministic versions of the models utilizing different assumptions concerning the opportunity cost of labor and capital in the fishing industry and different assumptions concerning aversions to fluctuations in income. The stochastic version of the model is used to simulate the consequences of the different management strategies and derive probability profiles for important variables like catch, stock sizes, and profits.

Biological Model

The biology of cod is modeled with simple extensions of the exponential decay cohort model described in Beverton and Holt (1957) using the catch equation of Baranov (1918). As recommended in Anon. (1993c), recruitment is linked to spawning stock biomass at the time of spawning, SSB, using the Ricker stock-recruitment function (Ricker 1954), modified to account for cannibalism by components other than spawning stock (*i.e.*, the immature cod biomass, J, at time of spawning), as in Pope and Woolner (1981), Pope (1992), and Bogstad *et al.* (1993). In the resulting equation, J occurs as a multiplier of natural mortality. The resulting stock-recruit model is:

$$R_t = \varsigma S_t \exp(-S_t/\kappa - \xi J_{t+1}) \tag{1}$$

where R is recruitment and S is spawning stock biomass. Greek letters denote parameters that must be estimated and the subscript t indicates the location of the variable in time, calculated in years.

The model is made stochastic by adding random components to account for recruitment variability and other sources of uncertainty using the suggestions set out in Anon. (1993c). Equation (1) has three parameters, all of which are estimated assuming log-normal recruitment (yielding $\varsigma = 1.46$, $\kappa = 764$, and $\xi = 0.69$). In this model the

[1] Apart from the authors of this paper, the members of the joint working group were: Brynjolfur Bjarnason, Chairman of the board of the Marine Research Institute and Chairman of the working group, Jakob Jakobsson, Managing Director of the Marine Research Institute, and Thordur Fridjonsson, Managing Director of the National Economic Institute.

biomass of immature fish, aged 3–14 years (J_{t+1}), is used as an index to approximate the biomass of immature fish of age 2 or more in year t, when the cohort is spawned.

Given equation (1), and the rest of the model for cod, there exists a steady state relationship between R and S for a given fishing mortality rate, where R is a concave function of S with a maximum of 240 million recruits when the spawning stock is around 800,000 tons.

Uncertainty in parameter estimates in the recruitment function is included by using the estimated variance-covariance matrix from the above estimation procedure. Thus, at the start of each simulation, a set of stock-recruitment parameters was generated from assuming a multivariate normal distribution of ($\ln \varsigma, 1/\kappa, \xi$). This set was then used to generate a time series of recruitment in that particular simulation.

Growth of cod is modeled by linking mean weight of each cohort in a given year linearly to mean weight in the year before and the size of capelin stock as in Steinarsson and Stefansson (1991). Effects of the capelin stock on the growth of cod have only been observed for ages 4–8. For other ages, a different model is needed and average growth is applied to obtain predicted weight of each cohort before applying density-dependent effects as described below.

The initial values for maturity and weight of each cohort, the selection pattern for 1993, and the initial stock size in 1994 by age group were based on Anon. (1993a) and revised in accordance with available information from surveys and catch up to spring 1994. The mature proportion in each cohort was at a high level in 1993 and therefore these values were assumed to decrease in 1994 halfway to the long-term mean; they were then used from 1995 onwards.

In stochastic simulations, initial stock size was based on random perturbations from the estimates given in Anon. (1994). In Anon. (1993b) the stock is determined by estimating a single fishing mortality multiplier but fixing the selection pattern to equal the average of some earlier years. Hence, stock estimates for different age groups will be positively correlated. The level of correlation will vary depending on the assessment method used, but it is likely to be high regardless of the particulars of the method, simply due to possible year effects in the survey data. Random perturbations are therefore obtained by drawing from a log-normal distribution with a standard deviation of 0.15 (along the lines of Gudmundsson 1994) and multiplying the entire initial stock-numbers for each cohort by this random number, except for the youngest cohort. The selection pattern was assumed to be known and fixed and equal to the selection pattern estimated for 1993. To generate random fluctuations in recruitment, the recruitment function was multiplied by a log-normal random variable with standard deviation 0.35, which is in accordance with the observed CV of recruitment.

Recruitment estimates for 1993–95 are based on surveys. Estimated recruitment for the years 1993–95 is 144, 73, and 130 million individuals, respectively (Anon. 1993a, 1993c). These estimates are taken to be intermediate in precision between future and historical levels and were multiplied by a log-normally distributed random variable with standard deviation 0.25. The additional groundfish survey information on age groups 3–5 in the initial year (1993) is incorporated by assuming the 3-year-old cod in numbers to be estimated with a 0.2 standard error based on the groundfish survey, and by assuming that the VPA-generated fishing mortality table is correct. This choice of simulating the estimation and recruitment variation is one of several possibilities mentioned in Anon. (1993c).

As noted in Baldursson, Danielsson, and Stefansson (1996), care needs to be taken when models indicate that the SSB of cod may increase to 1 million tons or more, which is greater than has been observed historically. In particular, density-dependent growth is likely to occur. In order to accommodate this, the effect of density-dependent growth along the lines indicated in Schopka (1993) is assumed. When SSB is below 500,000 tons, the size of the stock is not assumed to have any effect on the weight of the indi-

vidual fish, but when the SSB reaches a million tons the weight is assumed to drop to 70% of the maximum. This is implemented using a fraction which is related with a logit function to SSB in the range 500,000 to 10 million tons, but the result is an almost linear decrease from 1.0 to 0.7 for SSB in the historical range of 500,000 to 1.5 million tons.

The capelin dynamics are simplified from the usual model with two cohorts to a single cohort model which is driven only by catch and natural mortality rates. Average natural mortality for capelin in the years 1978–87 was estimated to be M = 0.035 using acoustic measurements (Vilhjalmsson 1994). Predation by cod on capelin is considerable and affects the capelin's natural mortality (Palsson 1983). This is modeled through simple scaling of M on juvenile capelin, along the lines of Pope and Woolner (1981). The scaling factor is taken proportional to the SSB for cod and set so as to correspond on average to acoustically measured natural mortality.

The capelin stock declined to very low levels twice in the 1980s, reaching minimum levels in 1982 and 1989 (Vilhjalmsson 1994) and there are some indications that the same may have occurred in the 1970s. For this reason it is assumed here that capelin recruitment is sinusoidal with a period of 7 years. For stochastic simulations, the period is taken to follow a distribution which is uniform on 5, 6, 7, 8, and 9 years, and recruitment is multiplied by log-normal random noise with a standard error of 0.20.

For shrimp, the dynamic stock biomass model defined and estimated in Stefansson, Skuladottir, and Petursson (1993) is used, albeit with some minor changes. This is a stock-production model incorporating measured recruitment and predation by cod:

$$B_{t+1} = \alpha B_t - Y_t + \beta R_t - D_t \tag{2}$$

where B is shrimp biomass, Y is catch, R is recruitment, and D is shrimp biomass consumed by cod and assumed proportional to the immature cod since this component of the cod stock overlaps spatially to a considerable extent with the shrimp stock. Historical recruitment and consumption by cod are estimated based on indices of the two quantities, but future values of both recruitment and consumption are based on regression estimates of the relationship with the biomass of immature cod.

TAC Rules and Utility

In order to evaluate different methods of harvesting the stocks involved, formal procedures were defined for the take from each stock. Such a procedure will be called a TAC rule.

The implementation of a TAC rule for cod in Icelandic waters requires extensive and clear communication to fishermen and the general public. This implies that the rule must be based on computations which the public understands, such as piecewise linear functions of spawning stock, fishable stock, and past catch. These considerations exclude nonlinear TAC rules, as well as rules based on fishing mortality rates. Short-term considerations and "political realism" may lead to the argument that there has to be some minimum restriction in the TAC rule, especially for important species like cod which is bycatch in a number of fisheries.

Cod

The TAC rule primarily tested for cod is given by the following formula:

$$Q_t = \min\left[\delta Q_{t-1} + (1-\delta)\max\left\{Q_{\min}, \min\left[Q_{\max}, a(\hat{S}_{t-1} - b)\right], Q_{1.5,t}\right\}\right] \tag{3}$$

where Q_{max} is the maximum TAC, Q_{min} is the minimum TAC, $Q_{1.5,t}$ is the catch obtained by setting the true fishing mortality rate in year t to 1.5, $\hat{S}_{t-1}$ is the estimated SSB in year $(t - 1)$ and δ, a, and b are parameters. Q_{max} was fixed at 450,000 tons, but Q_{min} was allowed to vary. The analysis of the optimal harvesting strategy gave the optimal steady state spawning stock at around 800,000 tons. An implemented TAC rule should therefore be such that the spawning stock tends to become this size. This gives one restriction on the values of the parameters a and b.

The precise speed of adjustment depends on some considerations discussed below, but in all cases considered optimal, adjustment consists of very low catch while SSB is recovering. When SSB approaches its optimal value, catch increases rapidly towards the long-run optimal catch. This would mean that b should be below, but close to, the optimal SSB of 800,000 tons and that a should be determined so that the catch rule gives the long-run optimal catch when SSB is 800,000 tons. In terms of figure 1, the TAC rule would follow the horizontal line of Q_{min} longer and then jump steeper than the dotted line to the optimal point of SSB of some 800,000 tons and annual catch near 356,000 tons.

In this paper it is assumed that the public is somewhat myopic and formula-aversive which makes it easier to get political support for an adjustment path when the catch increases earlier and more evenly than implied by the optimal path. One such path, given by $a = 0.45$ and $b = 50{,}000$ tons, is used in the calculations below.

Because of the high level of uncertainty in the stock estimates, a TAC rule which determines TAC solely on the basis of annual stock estimates will lead to great interannual variability in catch. The parameters Q_{max} and δ (and a) take this into consideration. δ takes values between 0 and 1. The value 0.5 is used in the trials discussed below.

The condition that fishing mortality rates do not exceed 1.5 was somewhat arbitrarily imposed. As this part of the rule becomes active only at very low stock sizes, economic considerations should lead to a halt in the fishing for cod long before the fishing mortality rate reaches 1.5.

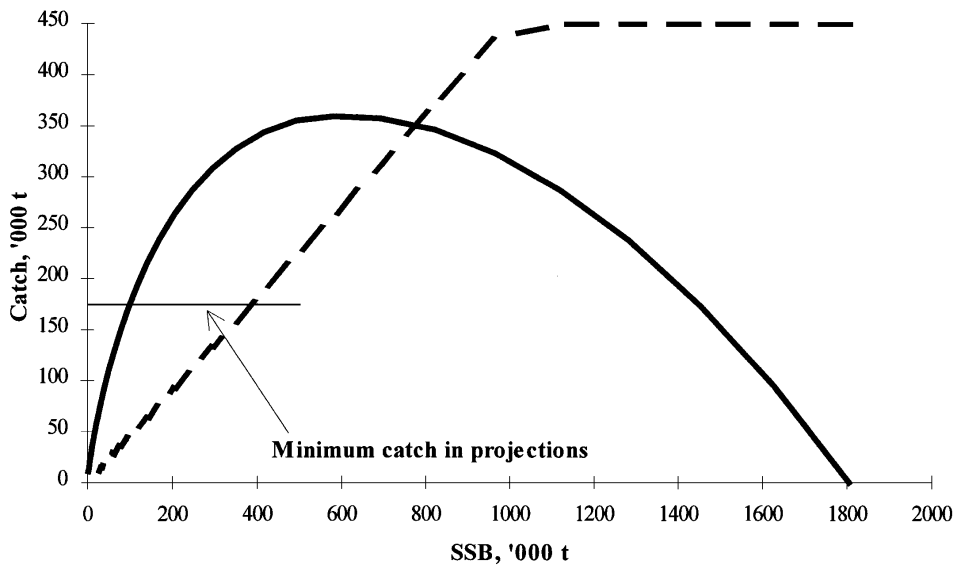

Figure 1. Steady State Catch and the TAC Rule

To take account of the inevitable future errors in the spawning stock estimate in any actual management, it was assumed that the estimated SSB was unbiased, but subject to a log-normal error with standard deviation 0.15.

Figure 1 shows the TAC rule as a function of the estimated spawning stock, assuming a minimum catch of 175,000 tons. Limitations on changes between years are not taken into account in figure 1 (*i.e.*, $\delta = 0$), nor is the curve which becomes binding at low stock sizes when the TAC rule is constrained by $F = 1.5$.

It is interesting to examine the historical development of the Icelandic cod stock in the context of steady state catch. This is done in figure 2 with fishable biomass as a measure of stock size. The figure clearly illustrates how stock has declined along with catch when catch was more or less consistently above the steady state catch curve. The clarity of this figure is somewhat surprising in view of the vast simplification embodied in the steady state catch curve. Also shown is the deterministically projected adjustment path using the TAC rule of figure 1 with zero minimum catch and $\delta = 0.5$.

Capelin

The capelin model assumes exploitation of the capelin stock in accordance with agreements between Iceland, Greenland, and Norway. These countries postulate a strategy aiming for a residual SSB of not less than 400,000 tons.

The capelin fishery can be split into two seasons: July-December and January-March. In the present implementation, catch of capelin influences stock size on January 1, and from there it influences the weight increase in the cod stock, but there is no interaction between capelin fishing in January-March and any other component of the model. Assuming that capelin fishing is profitable as a single-fleet, single-species fishery, it follows that any rule concerning the fishery in January-March will be optimized by catching the entire TAC for that period. It remains only

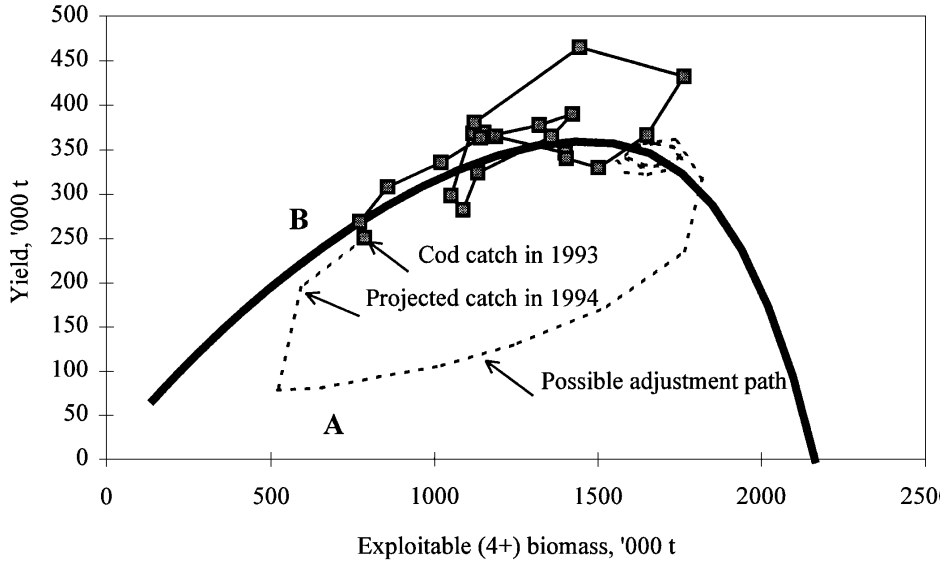

Figure 2. Steady State Catch and Historical Catch During 1973–94 Against SSB

to decide the proportion of the TAC to be taken in the fall season which is determined by the relative profitability of the fishery during these two periods.

During the past decade or so, natural mortality and individual growth of capelin have roughly canceled during the September-March period. This is used here to simplify the model by assuming that predation affects natural mortality only up to the time when the capelin enters the fishery. Alternative models might include heavier predation effects during the season and continuous effects of capelin biomass on cod growth, rather than the point-impact implemented here.

Shrimp

No formal harvesting strategy exists for the offshore shrimp stock. The approach taken was to use a TAC rule which keeps the biomass constant. In the present biological model, there is no incorporation of density-dependent factors which may lead to different production at one level of shrimp biomass compared to another. It therefore seems reasonable to expect that this TAC rule is close to being optimal within the present model.

Profit and Utility Functions

The prices used here are average prices for ungutted fish in 1993. For cod, the price of 110 Icelandic kronur per kg is used, for shrimp 140 kronur per kg, and the price of capelin is taken to be 7.75 kronur per kg during the period January-March, and 9.90 kronur per kg during July-December.

The following formula gives the price of cod exported from Iceland in year t:

$$P_t^G = P_0^G \left\{ (Q_{RoW}^G + Q_{Ice,t}^G) / (Q_{RoW}^G + Q_{Ice,0}^G) \right\}^{-1/\varepsilon} \tag{4}$$

where P_t^G and P_0^G are the prices of cod exported from Iceland in year t and 1993 respectively, Q_{RoW}^G is the supply of cod from the rest of the world (assumed 1.5 million tons), $Q_{Ice,t}^G$ and $Q_{Ice,0}^G$ are the catch of Icelandic cod in year t and 1993 respectively, and ε is the price elasticity which is estimated to be 2.0 (Danielsson 1993).

Product prices of shrimp and capelin are assumed constant. This assumption is made for simplicity rather than realism. It does not significantly influence the results of the paper.

It should be noted that the assumption of constant prices means that the capelin industry will be run at a loss during many years as it did in 1993. This could have been arbitrarily remedied by increasing the price so as to allow the capelin industry to break even. Instead, it was decided to keep the assumption of 1993 prices, and realistically, assume that the whole of the TAC for capelin would be taken each year even if it was done at some loss. Nothing of importance is lost by this approach.

The catch per unit of effort (CPUE) is assumed to increase with bigger exploitable biomass in the case of cod and shrimp. The elasticity of the CPUE for cod is important for the outcomes of the calculations, but as the TAC rule for shrimp is such that exploitable biomass remains almost constant, the elasticity for shrimp does not affect the results. Estimates of cost in fishing and processing in 1993 were used in the simulations.

It is assumed that wages of fishermen are fixed so that their relative pay compared to other workers does not change even though the profitability of the fishery they are participating in changes. As the fishermen in Iceland are paid a share, this is not a realistic assumption in the short-run. In an efficient labor market, however, the

parameters of the share-contract should adjust so as to make the expected pay equal to the opportunity cost of the fishermen's labor.

The following formula gives the profit of fishing and processing of cod in year t:[2]

$$\Pi_t^G = \left[P_t^G - \vartheta - \phi(BE_t^G)^{-\gamma}\right]Q_t^G \tag{5}$$

where Π_t^G is the profit in year t, BE_t^G is the exploitable cod stock where the weight of individual cohorts have been weighted with selectivity of the gears used, and ϕ, γ, and ϑ are parameters. ϕ is the cost of one unit of effort which is assumed to be constant. The elasticity of CPUE with respect to BE_t^G, $\gamma = 0.7$, is the estimate for trawl, the most commonly used gear in the cod fishery (Helgason and Kenward 1985). Results in Danielsson (1994) indicate that this number is not too high. The cost of processing one kg of cod, ϑ, is set at 48.40 kronur based on estimates for the average cost of processing in 1993.

Profits from fishing and processing shrimp and capelin are determined in a similar way as profits from fishing and processing of cod. The elasticity of CPUE with respect to the size of shrimp biomass is assumed to be 1. This assumption has no significant consequences as the TAC rule for shrimp ensures that the biomass of shrimp is almost constant during the simulated period. The elasticity of CPUE with respect to the biomass of the capelin stock is assumed to be zero, so in spite of considerable variations in the size of the stock, the profit from fishing and processing one unit of capelin is almost constant. Table 1 summarizes these assumptions.

Fishermen targeting haddock or saith or even shrimp often get some cod as bycatch. It is also very difficult to estimate the exact share of the different fisheries in actual costs of vessels which commonly target a number of species. In this paper, only cod, shrimp, and capelin are included, and rather crude methods have been used to estimate the cost of fishing for these species in the total costs. Because of the dominance of cod in the Icelandic groundfish fisheries, it seems reasonable to expect that the cost of fishing for cod is well estimated and the model should be able to produce some relevant results even if it leaves out some species that are fished to some extent together with cod.

In the model, all costs were assumed variable except in the capelin fishing and processing where there is a fixed cost which amounted to 1.50 kronur per kg in 1993. Instead of trying to incorporate the cost of adjustment explicitly into the model by assuming some fixed cost and some cost for the unemployment of labor, we decided to tackle these problems by using different objective functions.

No stochasticity was associated with the economic price or cost variables in the model, the most important of which are the prices of products and some inputs (*e.g.*, oil). As a result, the simulated dispersion in the economic results is somewhat smaller than what is realistic to expect.

The optimal harvesting strategy is found by first calculating the long-run optimum stock size and catch levels. The criterion used is maximization of the sum of discounted profits in a deterministic version of the model. This gives optimum stock sizes which are somewhat smaller than would have been found if the stochastic version of the model had been used and the sum of discounted utility from profits of a risk-averse owner with a concave utility function had been used as an objective

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[2] Equation (5) implies that the following relationship is assumed to exist between the catch of cod (Q_t), the effort of fishing for cod (E_t) and the exploitable biomass of cod (BE_t): $Q_t = qE_t(BE_t)^\gamma$, where q is the so called catchability coefficient. By suitable choice of units for E_t (given the value of γ and the units for BE_t), the value of q can be set equal to unity. It is now easy to solve for effort in this equation and multiply with the cost of one unit of effort (ϕ) to get the last part of equation (5).

Table 1
Values for Parameters in the Profit Function (5)

	P_{1993}	ϑ	$\phi(BE_{1993})^{-\gamma}$	γ
Cod	110.00	48.40	62.14	0.7
Shrimp	140.00	34.60	100.96	1.0
Capelin	8.83	3.50	4.58	0.0

function. After finding long-run optimum stock and catch levels, the optimal harvesting strategy is found using an adjustment period which is somewhat arbitrarily assumed to last eleven years. The optimal harvesting strategy during this adjustment period takes some account of the present situation of unemployment and excess capacity. This was done by using income instead of profits in the utility function, which is equivalent to assuming the cost of labor and capital to be zero during the adjustment period (as detailed in Baldursson, Danielsson, and Stefansson 1996) and maximizing the sum of discounted utility so defined. This approach assumes that it is not possible to completely avoid some decline in consumption because of a decline in catch and income while the cod stock is recovering. The importance of the cod fishery in Iceland makes this unavoidable. Aversion to fluctuations in consumption is taken into account by using a concave utility function. The form assumed for the instantaneous utility of consumption is the constant relative risk (or fluctuation) aversion form. As the consumption in Iceland is highly correlated with export income (Baldursson 1993) this income (y) is substituted for consumption in the utility function:

$$u(y) = (y^{1-\sigma} - 1)/(1 - \sigma) \tag{6}$$

where σ is the coefficient of relative risk aversion. Values of σ ranging from 0 to 6 were used in the calculation. Common values in econometric studies are in the vicinity of 2 (Lucas 1987).

Steady State Characteristics and Basic Conclusions

Biological Results

In order to understand the model characteristics, it is useful to examine its steady-state characteristics. As there is no true steady-state in the current model, because of assumed fluctuations in the recruitment of capelin, the last seven year average is used.

Depending on the state of nature and the selection of $Q_{\min}$, there may be up to four intersections of the steady-state catch and the TAC rule (figure 1). The two curves always intersect at the origin and one value corresponding to a stable equilibrium at a level of SSB around 800,000 tons. However, it is possible for the two curves also to intersect at one or two other points and this depends on the slope at the origin of the two curves. First suppose the slope at the origin of the steady-state curve is low, so that fishing mortality rate (F) of 1.5 will crash the stock. Then the $Q_{\min}$ line will intersect the steady-state curve and the $F = 1.5$ curve (not shown in figure 1) continues to the origin, staying above the steady-state curve. If the steady-state curve has a steep slope at the origin so that the stock can withstand a fishing pressure corresponding to $F = 1.5$, then a high $Q_{\min}$ value may cross the steady-state curve but the $F = 1.5$ line will cross it again, going to the origin below the steady-state curve.

The effect of lowering $Q_{\min}$ in the TAC rule for cod is that the speed of recovery of

the cod stock increases, and optimal TACs are allowed earlier. Setting Q_{min} to 220,000 tons will lead to a decline in the stock. As seen later, the effects of changing the other parameters in the TAC rule for cod are minor compared to the effects of changing Q_{min}.

A recovery of the cod stock will lead to a decline in TACs for capelin as would be expected. TACs for shrimp can be expected to decrease the most during the first years of a recovery of the cod stock and then increase later. The reason for this somewhat counterintuitive result is that it is the juvenile cod which feed on the shrimp, while the older cod do not, and the juvenile cod become less abundant at large stock sizes. This effect is more pronounced if the cod catch is cut drastically.

Economic Results

Results from optimization over harvesting policies using different economic criteria are given in table 2. The optimization was done using the annual fishing mortality rates as variables. The resulting catches are shown in the first part of table 2.

From an economic point of view, maximizing discounted profits is the obvious criterion for choosing the optimal harvesting strategy. It can, however, be argued that this criterion ignores the unemployment and the excess capacity that may exist and which mean that the actual market prices do not correctly reflect the opportunity cost of using labor and capital. These considerations will obviously change with the general economic conditions, not only in the fishing industry, but in the economy as a whole. It therefore seems reasonable to use the sum of discounted profits as a criterion to decide on the long-run stock level and catch, but to choose an adjustment path which takes some account of the specific economic conditions prevailing during some adjustment period. In the calculations presented in table 2, the length of the adjustment period was set at eleven years, starting in 1995 and ending in 2005. In the calculations, the recruitment of capelin was assumed constant and set at the estimated average. Throughout the calculations, a 5% discount rate was used. In Baldursson, Danielsson, and Stefansson (1996) different interest rates were used with no significant effect on the results. A higher rate of interest will result in a somewhat lower optimal stock size and an optimal adjustment path with somewhat higher catch and slower adjustment to the optimum during the first years.

The second section of table 2 shows the size of the spawning stock of cod. Figures for 2023, the last year in the calculations, show the optimal size. The third section of the table shows the exploitable biomass, and the fourth shows the fishable biomass. The fifth section shows the present value of profits from fishing and processing of cod, given the different harvesting strategies. These figures are estimates of the economic value of the resource. The calculations show that harvesting strategies which lead to a recovery of the cod stock to its optimal size will increase the value of the resource by some 60 billion kronur to some 255 billion kronur or US$3.6 billion. The sixth section shows the present value of profits from fishing and processing of cod, capelin, and shrimp. These figures are smaller than those for cod alone as the capelin industry in the model operates at a loss on the basis of 1993 prices. Sections seven and eight show the estimated decrease in the exploitation of capelin and shrimp as the cod stock is allowed to increase.

In the calculations presented in table 2, unemployment of labor and capital is taken into account by maximizing income during the adjustment period of eleven years (column 3-5). This is equivalent to assuming that, because of the unemployment, the cost of using these factors is zero, an assumption which is obviously extreme. Yet in all cases the calculations indicate that it is highly beneficial to reduce fishing immediately and drastically. The calculations give a value of optimal SSB in the range 750,000–850,000 tons. It is also worth noting that the cost of taking ac-

Table 2
Optimization Results

	(1)	(2)	(3)	(4)	(5)
Cod Catch*					
1993	251	251	251	251	251
1994	190	190	190	190	190
1995	0	0	0	82	84
1996	0	0	95	106	106
1997	36	75	164	133	133
1998	176	193	190	166	165
1999	253	260	219	199	199
2000	278	287	249	231	230
2001	299	307	274	255	255
2002	322	326	290	271	270
2003	333	337	299	281	281
2004	330	336	307	292	291
2005	345	356	356	356	356
2023	347	356	356	356	356
Cod SSB*					
1994	223	223	223	223	223
2023	835	763	762	762	762
Exploitable Biomass*					
1994	346	346	346	346	346
2023	1,473	1,378	1,378	1,378	1,378
Fishable Biomass*					
1994	593	593	593	593	593
2023	1,668	1,612	1,612	1,612	1,612
Present Value of Profits from Fishing and Processing of Cod**					
1994	201	200	196	192	191
2023	258	255	255	255	255
Present Value of Profits from Fishing and Processing of Cod, Capelin, and Shrimp**					
1994	194	195	193	189	189
2023	246	245	245	245	245
Capelin Catch*					
1994	896	896	896	896	896
2023	323	385	385	385	385
Shrimp Catch*					
1994	64	64	64	64	64
2023	29	28	28	28	28
Effort in Fishing for Cod (index)					
1994	100	100	100	100	100
2023	66	71	71	71	71

Notes: (1) The sum of discounted profits from fishing and processing of cod is maximized. (2) The sum of discounted profits from fishing and processing of cod, capelin, and shrimp is maximized. (3) Adjustment to profit-maximizing stock and catch levels during eleven years, the path of adjustment is decided by maximizing the discounted value added. The profits are calculated on the basis of historical costs, not taking into account the implied opportunity costs of labor and capital during these eleven years. (4) As in (3), but the adjustment path is decided by maximizing discounted utility with moderate risk aversion ($\sigma = 2$). (5) As in (3), but the adjustment path is decided by maximizing discounted utility with high risk aversion ($\sigma = 6$).
* Units in '000 tons; ** Units in billions of kronur.

count of the present situation of unemployment and overcapacity, together with aversion to fluctuations, is relatively small. By comparing the present value of profits from fishing and processing of cod, shrimp, and capelin in column (2) and column (5), we see that this cost is 6 billion kronur (195 – 189). The cost in terms of profit foregone in fishing and processing of cod is higher, 9 billion kronur (200 – 191).

Table 2 shows that the optimal SSB is 835,000 tons when the sum of discounted profits from the fishing and processing of cod is maximized, while it is 763,000 tons when the sum of discounted profits from fishing and processing of cod, shrimp, and capelin is maximized.

The optimizations presented above are done with a deterministic version of the model where the cost of increased variability in income which follows from fishing from a small stock is not taken into account. A stochastic optimization would give an optimum strategy with somewhat smaller catch and faster recovery of the cod stock than is shown in columns 3–5 in table 2 (Baldursson and Magnusson 1997).

Simulation Results

To analyze the characteristics of a TAC rule, it is often interesting to study the probability of a collapse. Here, the cod stock is said to collapse if it declines below 100,000 tons. Results from the simulations show that the size of the cod stock, by the end of the period, has a bimodal distribution with no mass in the interval from 50,000 to 150,000 tons making the precise definition of the collapse cut-off point less important. The probability of a collapse is zero when $Q_{\min} \leq 140{,}000$ tons, but increases fast thereafter. It is 3% when $Q_{\min} = 165{,}000$ tons and 20% when $Q_{\min} = 190{,}000$ tons. Further details of the results from a TAC rule where catch is maintained above 165,000 tons as long as possible are presented in figure 3.

The trajectory diagrams in figure 3 contain several different line types. The thin lines show simulated trajectories for five sample simulations. The central solid thick line denotes median value from the 300 simulations conducted. The top and bottom solid thick lines indicate lower and upper 5% of the distribution of results and finally, the dashed thick lines depict upper and lower 25th percentiles. For example, the top left panel shows results concerning SSB for cod from 300 simulations. It is seen that there is a 50% chance that the spawning stock will still be below 200,000 tons in 1997. It is also seen that there is less than a 5% chance that the stock will decline towards zero (the estimated probability is 3%). A summary of economic results from the simulations is given in table 3.

The mean of simulated present values of profits in table 3 can be compared to the present value of profits from the optimal harvesting path in column (2) of table 2.

Table 3
Economic Summary for the Base Case

Cum. Probability	Gross Revenues	Profit	GDP Contribution
5%	717	98	487
25%	749	132	516
50%	767	150	535
75%	782	161	548
95%	806	179	570
Mean	760	141	526
Std. deviation	44	46	47

Notes: Units in billions of kronur. Minimum catch set to 165,000 tons. Present value using 5% discount rate.

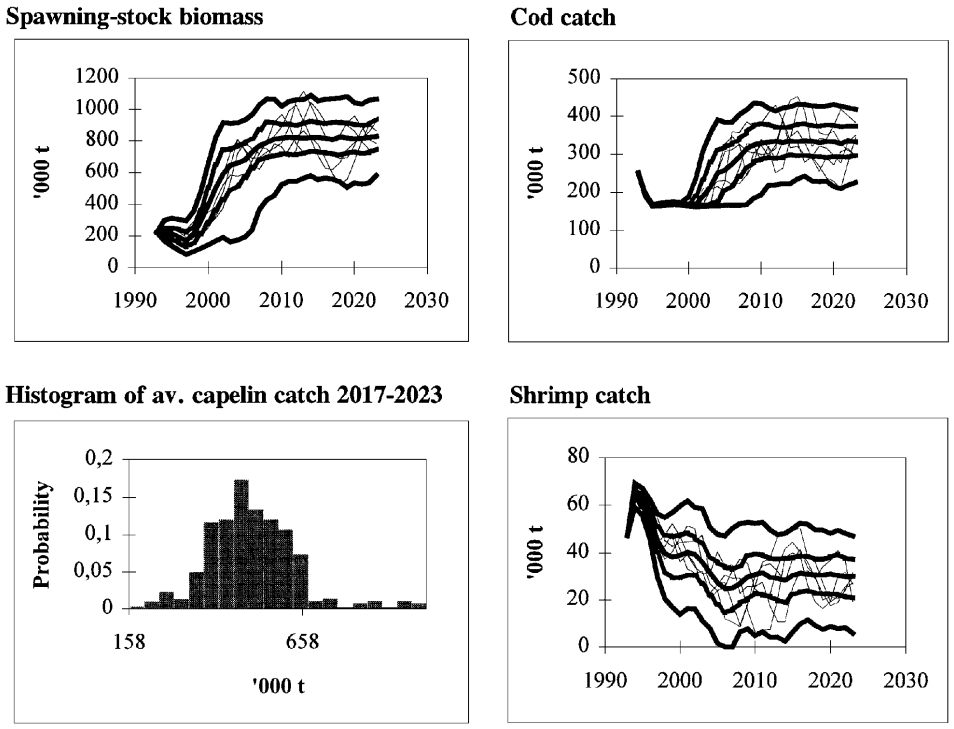

Figure 3. Simulation Results. SSB-Based TAC Rule and Minimum Cod Catch of 165,000.

The cost of the TAC rule, which can be approximated by the difference between these two present values is 54 billion kronur (195 – 141). Most of this cost can be blamed on the minimum catch of 165,000 tons of cod.

Sensitivity Analysis

It is of interest to consider the effect of changing some of the assumptions in the model above, or including some missing sources of variation. Table 4 gives the results from this analysis. The following changes in the TAC rule were considered: Q_{min} = 140,000 tons, Q_{min} = 190,000 tons, $\delta = 0.25$, and $\delta = 0.75$. A new TAC rule was tested based on fishable biomass (age 4 and older) rather than SSB. The proportion (22%) is decided so as to give the same long-term equilibrium as the SSB-based rule above. Although it would usually be considered more appropriate to use SSB as a basis for a TAC rule, the reason for testing a different biomass rule is twofold: First, it is simpler than equation (3) above, and second, it avoids the use of the proportion mature, which is notoriously hard to estimate (Anon. 1994).[3]

Table 4 also shows results from assuming that recruitment to the cod stock was

[3] The working group mentioned in the introduction decided eventually, on the basis of these arguments, to recommend that the annual TAC should be set equal to the average of last year's catch, and 22% of the estimated fishable biomass, but not lower than 155,000 tons.

Table 4
Sensitivity Analysis

	A	B	C	D	E	F	G	H	I	J	K	L	M
Base Case													
(Q_{min} = 165,000)	3.0%	2000	96.7%	2007	806	328	30	509	31	141	46	526	47
Modifications of the TAC Rule													
Q_{min} = 190,000 tons	20.0%	2000	77.7%	2008	664	275	26	588	40	93	95	489	94
Q_{min} = 140,000 tons	0.0%		100.0%	2005	834	340	31	494	29	155	17	534	21
Previous year weight = 0.25	3.0%	2000	96.7%	2006	805	329	45	509	31	141	46	527	47
Previous year weight = 0.75	3.0%	2000	96.7%	2008	801	328	16	512	31	140	46	521	45
Fishable biomass rule	3.0%	2001	96.7%	2007	763	332	28	540	30	139	45	535	48
Modification of the Biological Assumptions													
Growth independent of dens	5.0%	2002	94.3%	2007	797	333	26	517	25	139	56	523	56
Recruitment 10% higher	2.0%	2001	97.3%	2006	863	348	30	469	28	152	40	541	41
Recruitment 10% lower	4.7%	2000	95.3%	2008	742	305	29	552	34	128	52	508	53

Notes:
A = Probability of a collapse in the cod stock, *i.e.*, of a stock below 100,000 tons in 2024
B = Average year when the cod stock drops below 100,000 tons, in those simulations when this occurs
C = Probability that the cod catch exceeds 300,000 tons before 2024
D = Average year when the cod catch exceeds 300,000 tons, in those simulations when this occurs
E = Average cod SSB 2017–23, '000 tons
F = Average cod catch 2017–23, '000 tons
G = Average interannual changes in cod catch 2017–23, '000 tons
H = Average capelin catch 2017–23, '000 tons
I = Average shrimp catch 2017–23, '000 tons
J = Expected present value of profits in billions of kronur
K = Standard deviation of present value of profits in billions of kronur
L = Expected present value of GNP in billions of kronur
M = Standard deviation of present value of GNP in billions of kronur

10% higher and 10% lower than what was assumed in the base case. The overall conclusion from table 4 is that the only modification which has a major effect is a change in the minimum TAC. Increasing the minimum TAC to 190,000 tons will increase the collapse probability to 20% and decrease all expected benefits accordingly. Similarly, reducing the minimum TAC to 140,000 tons is expected to give higher gains (column J) and safer utilization of the resource (column A). It is also worth noting that greater "smoothing" of catches ($\delta = 0.75$) seems to have little effect on the results, other than the obvious ones of reducing the amplitude of interannual fluctuations in catches.

Discussion

The results indicate that overall gains from fishing for the three species considered in this paper can be enhanced considerably by an initial decrease in fishing for cod, which would allow the cod stock to recover. A long-term aim of maintaining the

SSB at about 800,000 tons and the fishing mortality rate around 0.3 would be suitable for this purpose. Several means exist to approach this goal. In particular, it is seen that the TAC rule with minimum cod catch of 165,000 tons would allow the cod stock to approach such a value with quite high probability. It is clear, however, that this result is quite sensitive and minor changes in the baseline assessment of the stocks can change the estimate of this probability considerably. If the baseline assessment is too high, then catching 165,000 tons of cod would entail a significant probability of a collapse in the cod stock.

The model in this paper shows that even though the probability of a collapse in the cod stock is very low when the minimum catch is 165,000 tons, a TAC rule with this minimum catch would entail considerable economic cost, compared to a rule with lower minimum catch.

These results are qualitatively similar to those obtained for the cod stock in Baldursson, Danielsson, and Stefansson (1996), where a single species model for cod was considered. In the present paper, the reduction in capelin and shrimp catch, due to an increase in the cod stock, is taken into account, as well as the potential effect of food shortage on the growth of cod. It is seen that these factors only marginally change the qualitative results for the cod stock alone, although the estimate of the optimum catch of cod increases a little and the optimal stock size decreases somewhat.

Earlier modeling work has indicated that cod may switch from capelin to other prey like shrimp in years of low capelin abundance. In the extreme case, cod could "overexploit" shrimp, with the net effect that the mean weights of the cohorts of cod decrease. This is partly accounted for in the density-dependent weight reduction in the cod stock, which does incorporate the type of weight reduction that has been seen in historical data sets. It seems worthwhile to use alternative models, *e.g.,* where the mean weights of the cohorts of cod are related to the biomass of capelin per unit abundance of cod. It does, however, seem unlikely that these alternative models will change the main conclusions of this paper.

The models in this paper use economic data for 1993 when the price of shrimp was low relative to the price of cod. Since then the price of shrimp has increased substantially while the price of cod has declined somewhat. The cost of allowing the cod stock to recover to its former size, in terms of foregone profits from fishing and processing shrimp, would therefore be much higher if today's economic data were used, instead of data for 1993. Somewhat counterintuitively the model predicts that an increase in the price of shrimp relative to the price of cod will lead to an increase in the optimum size of the cod stock. This is due to the enormous profitability of the fishing and processing of cod when the stock has recovered and the Rickerian effect that at large stock sizes the juvenile stock, which feeds on shrimp, will actually decrease when the cod stock grows, allowing an increase in the catch of shrimp at the cost of some decrease in the catch of cod. Even large changes in the relative price will not change the optimum size of the cod stock much, but the profits and the value of the natural resource will change substantially.

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