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Economic impacts of changes in the population dynamics of fish on the fisheries of the Barents Sea

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A bioeconomic simulation model of the two interacting fish species cod (*Gadus morhua*) and capelin (*Mallotus villosus*) and their fisheries is presented and applied to assess the consequences of changes in the population dynamics of these important fish stocks in the Barents Sea. In each scenario, the population dynamics of the fish species are changed by reducing the reproduction-induced productivities and/or the carrying capacities. Stock sizes and landings of fish are calculated for each fishing period, and the net present values of profits from fishing are determined for time periods prior to and after the change in population dynamics. Results show that reduced growth rates or carrying capacities lead to lower stock levels and consequently to smaller catches. There is only a small short-term economic impact on the fisheries, but the long-term consequences are pronounced. In some cases, greater fishing activity in the first few years after the change in population dynamics causes harvests to remain stable despite diminishing stock sizes. This stabilizes the returns from fishing in the short term, but veils the apparent negative long-term impact on the fisheries resulting from adversely affected stock dynamics.

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Introduction

The size and the geographic range of fish stocks depend largely on existing hydrographic conditions. Changes in temperature, salinity, or oxygen content can have adverse effects on the fish stock population dynamics, sometimes even causing stocks to collapse, especially when they are subjected to fishing. Therefore, it is important in an assessment of the population dynamics of fish stocks not only to consider economic exploitation, but also to allow for sudden changes brought about by altered climatic and oceanographic conditions. While the models currently used to assess fish stocks account for a variety of environmental conditions as well as effects of changes in different compartments of the ecosystem, such as food availability or predator abundance (ICES, 2003a,b), they disregard the impacts of long-term change in hydrographic conditions, such as shifts initiated by, for example, a weakening of the thermohaline circulation (THC), because the models are normally used for short-term predictions of the dynamics of fish stocks.

Studies of stock trajectory as a function of environmental conditions indicate that recruitment success of cod (*Gadus morhua*) increases with warmer average water temperatures (Nilssen *et al.*, 1994; Ottersen *et al.*, 1994) for a given spawning-stock biomass, whereas year classes tend to be smaller during colder years. A change in hydrographic conditions towards colder temperatures in the Barents Sea attributable to a weaker THC would therefore adversely affect recruitment success and thus the overall stock trajectories of Barents Sea cod. The capelin (*Mallotus villosus*) stock would be similarly affected by such a change in the Barents Sea temperature regime, because reduced food availability would negatively influence the growth of individual capelin as well as the overall stock size (Skjoldal *et al.*, 1992). Such stock size reductions inevitably have an effect on the fisheries of both species.

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This study uses a bioeconomic simulation model to assess the economic impacts that a sudden change in the fish population dynamics would have, focusing on the Barents Sea cod and capelin fisheries. The model covers a time period of a century and looks at the economic effects of changes in the population dynamics of fish stocks, namely the intrinsic rate of production and the environmental carrying capacity. Cod and capelin fisheries were selected because the cod fishery is of great economic importance in Norway, and capelin are one of the main food sources of cod. Therefore, changes in the Barents Sea capelin stock would have an effect on the cod stock as well. For the purpose of this analysis, the fisheries of cod and capelin in the Barents Sea are introduced and existing studies that apply bioeconomic models to the fisheries in the Barents Sea are reviewed. The model used for the analysis and the data applied are presented, and results of the simulations given. Later, we discuss the consequences that a severe change in fish population dynamics would have on the fisheries for Arcto-Norwegian cod and Barents Sea capelin.

Background

Cod and capelin fisheries in the Barents Sea

The Arcto-Norwegian cod stock, also referred to as the Northeast Arctic cod stock, is the most valuable fish stock in the Barents Sea. It is the most abundant of the Atlantic cod stocks, and is one of the most commercially important fish stocks worldwide (Sumaila, 1995). Arcto-Norwegian cod prey mainly on capelin, herring (*Clupea harengus*), haddock (*Melanogrammus aeglefinus*), young cod, shrimp (*Pandalus borealis*), and other invertebrates (Mehl, 1989).

In the past, the size of the Arcto-Norwegian cod stock has varied significantly. Overall, total biomass declined from more than 3 million tonnes in the 1950s to roughly a million tonnes in the 1980s, probably driven by increased fishing (ICES, 2003a). Short-term increases in the total biomass only occur when there has been particularly successful recruitment to the stock (Mehl and Sunnanå, 1991); such was the case when cod increased to >2 million tonnes in the early 1990s.

Annual catches of Arcto-Norwegian cod fluctuated between 400 000 and 1 200 000 t until the late 1970s (ICES, 2003a), then declined to roughly 400 000 t, coinciding with the reduction in stock size, before recovering at the beginning of the 1990s, when the stock again became abundant. At present, there are about 60 Norwegian trawlers and 640 small coastal vessels engaged in the fishery (Statistisk Sentralbyrå, 2002). Recent annual catches of Arcto-Norwegian cod amount to roughly 270 000 and 130 000 t from trawlers and coastal vessels, respectively.

The Barents Sea capelin stock is also of great importance, not only commercially, but because it is one of the main prey species of cod. Data on capelin show that between 1972 and 1984, the size of the stock was relatively stable at around 4 million tonnes (Gjøsæter *et al.*, 1998), before being reduced to <200 000 t in the mid-1980s and mid-1990s. Although there have been periods of quick recovery, they did not last long, because the sharp increases in capelin biomass, e.g. in the early 1990s, can be attributed to the recruitment success of just one or two year classes.

Annual catches of Barents Sea capelin amounted to more than a million tonnes during the stable period of the capelin stock size until the mid-1980s. The stock then collapsed within two years, forcing closure of the fishery until 1990 (Gjøsæter *et al.*, 2002). For the short period of stock recovery the fishery was re-opened, but catches were fairly low. Fishing activities ceased again from 1994 to 1998. The subsequent increase in stock size was rather short-lived, so harvesting of Barents Sea capelin was only possible for a few years. When the stock decreased recently the fishery was again closed, because the capelin harvesting strategy calls for the total allowable catch (TAC) to be set such that the probability of the spawning-stock biomass remaining above a threshold of 200 000 t is 95% (Commission of the European Communities, 2005). Because of the stock's great variability, a capelin TAC based on such a strategy needs to be set to zero quite often. Exploitation of cod and capelin stocks is managed jointly by Norway and Russia. The Joint Norwegian–Russian Fisheries Commission splits TACs and divides the quotas among the countries. In 2004 and 2005, the TAC for Arcto-Norwegian cod was 486 000 and 485 000 t, respectively (Michalsen, 2004; Commission of the European Communities, 2005). However, owing to the poor current state of the capelin stock, both countries agreed to refrain from fishing capelin in 2004 and 2005.

Bioeconomic modelling of Barents Sea fisheries

Modelling studies of the Barents Sea fisheries have focused on both the biological and the economic consequences of different management strategies or different economic regimes. The single-species model CAPELIN was a first attempt to simulate the trajectories of capelin stock size (Tjelmeland, 1985), being used to determine the harvest that would lead to optimal further enhancement. However, any focus on a single fish species has the disadvantage that species interactions will be neglected. Therefore the model BIFROST (Gjøsæter *et al.*, 2002) was developed to assess the short-term trajectory of the capelin stock, focusing on management of capelin only without neglecting species interactions.

Aggregated versions of the multispecies models ECONMULT (Eide and Flaaten, 1993) and MULTSPEC (Bogstad *et al.*, 1997) were developed for management purposes: the models were ECONSIMP and MULTSIMP (Eide and Flaaten, 1994). Analyses with these models show that it is economically advantageous to catch both cod and capelin, instead of just harvesting the more valuable cod and leaving the capelin in the sea as additional food source for cod. Moxnes (1992) included uncertainty in his analyses

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for the Barents Sea, and showed that considering the uncertainty arising from random variations, measurement errors or uncertain parameters can have a pronounced impact on model results and, thus, also on management decisions.

Sumaila (1995) used a bioeconomic model of the Barents Sea cod fishery that considers different fleet types to determine the size of the fishing fleets necessary to exploit the cod stock optimally. Application of an expanded version of this model, including a predator–prey relationship between cod and capelin, showed that a joint strategy of harvesting both fish stocks leads to substantially higher profits from fishing than uncoordinated and competitive exploitation (Sumaila, 1997).

Eide (1997) and Armstrong and Sumaila (2000) analysed the influence of cod cannibalism on the cod fisheries. Results showed that economically optimal use of the cod stock can only be achieved if the impact of cannibalism is acknowledged (Eide, 1997). According to these analyses, the present share of the cod trawlers should be reduced in favour of the smaller coastal vessels, because the latter generally target older cod than the trawlers (Armstrong and Sumaila, 2000), leading to improved economic results in the long term. Armstrong and Sumaila (2001) assessed the distribution of Barents Sea cod TAC among trawlers and coastal vessels and the implications of a possible introduction of individual transferable quotas (ITQs). They showed that ITQ introduction would not result in a significant improvement of the economic output owing to possible negative effects arising from one fleet type buying up all the quotas.

All studies listed above analyse aspects of the Barents Sea fisheries. However, environmental change is not addressed specifically in any of the models. Indeed, it is seldom addressed (Knowler, 2002). Changes in environmental conditions can affect fisheries population dynamics, which in turn have implications for economic output. This makes it necessary to account for changes in population dynamics when setting up a bioeconomic model that addresses long time horizons.

Methods

The simulation model

Generally, bioeconomic models are used to assess the magnitude of returns under different economic regimes, or to analyse optimal stock exploitation. Usually, the time horizon is only a few years and environmental conditions are considered to be constant.

The model described here covers two important fish species of the Barents Sea that are harvested commercially, cod and capelin (Figure 1). Cod prey on capelin. Two different fleet types are engaged in the cod fishery: large trawlers and smaller coastal vessels. Capelin are caught mainly by purse-seine; other means of catching capelin are of little importance and are therefore ignored for this analysis. The model assumes perfect market conditions and that the social net benefits are maximized. Both stocks are jointly managed by Norway and Russia, but we do not distinguish between fishers. Management schemes, such as quotas, are disregarded.

The time horizon is one century, and each fishing period lasts one year. Changes in stock size in each fishing period are attributable mainly to harvesting, natural mortality, predation, and recruitment. During the simulation, a change in productivity and/or carrying capacity takes place, forcing a change in recruitment and, in the long-term, stock trajectories. Variables concerning the economic exploitation of the stocks and population dynamics are calculated for each fishing period. By comparison with a reference scenario in which the productivities and carrying capacities remain unchanged, the economic impacts of changes in stock dynamics are assessed. In addition, sensitivity analyses using the reference scenario are conducted to determine the influence of changes in key parameters on the simulation results. These quantities are the share of capelin devoted to human consumption, the discount rate, and the extent to which new information on stock trajectories is utilized in determining the harvesting strategies of the fleets.

Population dynamics of cod and capelin

Cod and capelin stocks are divided into age classes: 15 for cod and five for capelin. Key equations of the model are listed in Table 1. The number of individuals in each age class and the stock biomass at the beginning of a fishing period are known (Equation (1)). Stock size is reduced through harvesting by the various fishing fleets (Equation (2)). Stocks interact via predation (Equations (6) and (7)) with the rate of cod weight increase depending on the extent of capelin consumption (Equation (8); cf. Magnússon and Pálsson, 1991). Average capelin weight-at-age is assumed constant.

Recruitment depends on the stock size at the end of the harvesting period (Equation (3)). The number of recruits (Equation (4)) is obtained using a Beverton and Holt recruitment model (Beverton and Holt, 1954) in which the parameters are set such that the equilibrium biomass of unexploited stocks in the reference scenario would be 6 million tonnes for cod (Sumaila, 1997) and 10 million tonnes for capelin. The age classes at the beginning of the next fishing period consist of the surviving individuals of the next younger age class in the previous year. Cod older than 14 years accumulate in the oldest "plus" age class (Equation (5)).

The fisheries

All fleets engage in harvesting during each fishing period (Equation (9)). It is assumed that the demand curve is elastic, i.e. the market price for both species remains constant regardless of the quantities landed. Some capelin is sold for human consumption at a higher price whereas most of the catch is used to produce fishmeal and fish oil; we use

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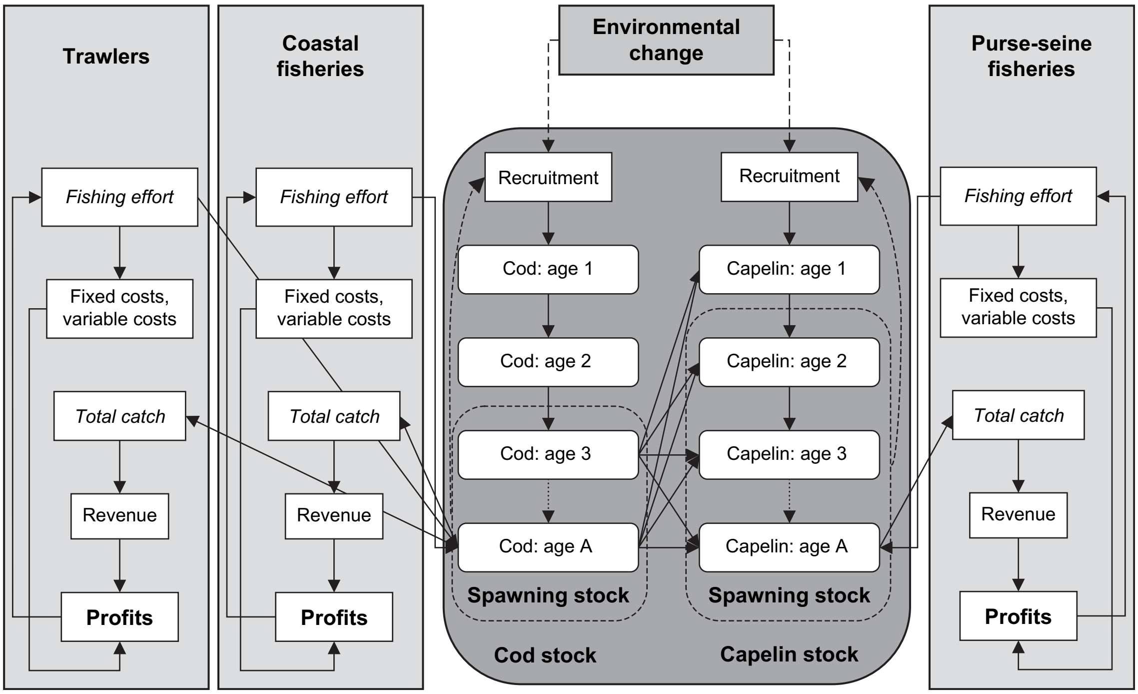

Figure 1. Structure of the simulation model.

a weighted average that is slightly above the capelin price for industrial use.

Profits of each fleet (Equation (12)) reflect differences between revenues from sales of landings (Equation (10)) and the total cost of fleet operation, consisting of fixed costs for fleet maintenance that are independent of fleet utilization and variable costs directly related to the extent of fleet utilization (Equation (11)).

In this study, profits from fishing during three different time periods of 15 years (the average lifetime of a vessel) each are of special interest: the period 30−44 years (i.e. a period before the change in population dynamics), 50−64 years (i.e. the period revealing short-term impacts of the change in population dynamics), and 70−84 years (i.e. a period in which long-term impacts of changes in population dynamics become evident). Profits are discounted at rate δ (Equation (13)). The control variable is the fishing effort. The boundary condition for the economic exploitation of fish stocks is the population dynamics of the two species.

Harvesting strategy

Each fleet's fishing effort (Equation (17)) is adjusted after each fishing period according to returns from fishing in the previous fishing period. This is done by comparing actual catch with a previously calculated target value of an expected harvest that can be determined based on the relationship between the unit costs of harvesting (Equation (15)) and stock trajectories (Equation (16); cf. Clark, 1990) assuming logistic growth (Equation (14)). If the amount of fish landed is less (more) than the target catch size, fleet utilization is increased (decreased) by 10% in the following fishing period.

The expected productivity of the fish stock, which is important in calculating the target value of catches, is also updated. This is done on the basis of the observed stock size trajectories (Equation (18)), which are used in a learning function (Equation (19)) to determine a weighted average of the actual and previously expected rates of productivity. This weighted average is then used as a basis for the same calculations in the next fishing period.

Results

A series of simulations was conducted to assess the consequences of changes in fish population dynamics on the fish stocks and the resulting economic impacts. All simulations covered a time period of 100 years. In each simulation, a sudden decrease in productivity or environmental carrying capacity was set to occur in year 50. The initial stock sizes were obtained using the average number of individuals in each age class during the time period 1983−2002 for cod (ICES, 2003a) and capelin (ICES, 2003b). An overview of the parameters used in the simulations is given in Appendix 2.

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Table 1. Summary of model equations. See Appendix 1 for symbols.

Population dynamics of the fish species

$$B^{\text{init}}_{s,t} = \sum_a w_{s,a,t} n^{\text{init}}_{s,a,t} \quad (1)$$

$$n^{\text{harv}}_{s,a,t} = n^{\text{init}}_{s,a,t} - \sum_i h_{s,i,a,t} \quad (2)$$

$$\text{SSB}_{s,t} = \sum_a \mu_{s,a} \text{sw}_{s,a} n^{\text{harv}}_{s,a,t} \quad (3)$$

$$R_{s,t} = \frac{\alpha_{s,t}\text{SSB}_{s,t}}{1 + \beta_{s,t}\text{SSB}_{s,t}} \quad (4)$$

$$\begin{aligned} n^{\text{init}}_{s,1,t+1} &= R_{s,t} \\ n^{\text{init}}_{s,a+1,t+1} &= \chi_{s,a} n^{\text{harv/pred}}_{s,a,t} \\ n^{\text{init}}_{\text{cod},A,t+1} &= \chi_{\text{cod},A} n^{\text{harv}}_{\text{cod},A,t} + \chi_{\text{cod},A-1} n^{\text{harv}}_{\text{cod},A-1,t} \end{aligned} \quad (5)$$

Predation and weight increase

$$D_{\text{cap},t} = \frac{D^{\max}_{\text{cap}}}{1 + \left(D^{\max}_{\text{cap}} - 1\right)\left(\frac{B^{\text{harv}}_{\text{cap},t}}{B^{\text{std}}_{\text{cap}}}\right)^{-\gamma}} \quad (6)$$

$$B^{\text{pred}}_{\text{cap},t} = \kappa_1 D_{\text{cap},t} B^{\text{harv}}_{\text{cod},t} \quad (7)$$

$$w_{\text{cod},a+1,t+1} = w_{\text{cod},a,t} + \widehat{w}_{\text{cod},a}\left(D_{\text{cap},t}\kappa_2 + (1-\kappa_2)\right) \quad (8)$$

Exploitation of the stocks

$$h_{s,i,a,t} = q_{s,i,a} n^{\text{init}}_{s,a,t} v_{s,i} e_{s,i,t} \quad (9)$$

$$r_{i,t} = \sum_{s,a} P_{s,i} h_{s,i,a,t} w_{s,a,t} \quad (10)$$

$$\psi_{i,t} = \varphi_i + e_{i,t}\theta_i \quad (11)$$

$$\pi_{i,t} = r_{i,t} - v_i \psi_{i,t} \quad (12)$$

$$\Pi_i = \sum_{t=t_0}^{t_0+14} \mathrm{e}^{-\delta(t-t_0)} \pi_{i,t} \quad (13)$$

Adaptive harvesting strategies

$$G^{\exp}_{s,t}\left(B^{\text{init}}_{s,t}\right) = g^{\exp}_{s,t} B^{\text{init}}_{s,t}\left(1 - \frac{B^{\text{init}}_{s,t}}{K_{s,t}}\right) \quad (14)$$

$$\Theta_{s,i,t} = \frac{\psi_{s,i}}{q_{s,i}B^{\text{init}}_{s,t}} \quad (15)$$

$$G'^{\exp}_{s,i,t} - \frac{\Theta'_{s,i,t} G^{\exp}_{s,i,t}}{P_{s,i} - \Theta_{s,i,t}} = \delta \quad (16)$$

$$e_{s,i,t+1} = \frac{g^{\exp}_{s,t}}{q_{s,i}v_i}\left(1 - \frac{B^{*}_{s,t}}{K_{s,t}}\right) \quad (17)$$

$$\overline{g}_{s,t} = \frac{B^{\text{init}}_{s,t} - B^{\text{init}}_{s,t-1}}{B^{\text{init}}_{s,t-1}} \quad (18)$$

$$g^{\exp}_{s,t+1} = \lambda_s \overline{g}_{s,t} + (1-\lambda_s) g^{\exp}_{s,t} \quad (19)$$

Reduction in productivity

A decline in the rates of cod and capelin reproduction-induced productivity leads to smaller stock sizes. The cod stock decreases by roughly one-third for a reduction in productivity of 50% (Figure 2). The periodicity of the fluctuation in stock size, which is a consequence of the rule of updating fishing effort of the fleets, increases substantially at smaller total-stock biomass. The capelin stock trajectory follows the same general pattern. In the reference scenario, the overall capelin stock biomass fluctuates around an average value of approximately 2 million tonnes. Reducing the productivity by 50% decreases the average stock size to roughly 1.5 million tonnes. The impact of the change in capelin productivity on the stock size becomes evident earlier than does a reduction in cod stock size owing to the much shorter lifespan of capelin and the fact that the change in population dynamics takes place at a point in time when the periodic trend of an increasing capelin stock size is suddenly reversed.

Because of the reduced stock sizes, annual cod and capelin catches decline. Compared with the reference scenario, in which annual trawl catches of cod fluctuate around 160 000 t and annual coastal vessel catches total slightly less than 100 000 t (Table 2), catches decline notably even for small reductions in productivity. The short-term decline in annual catches is slightly less than 10% for a small change in productivity, but reaches almost 20% for both fleet types when productivity is reduced by a larger margin. Comparison with a later simulation time period reveals that the short-term reduction in average annual catches is only the beginning of

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a negative trend that leads to a long-term decline in catches by more than 76% in some scenarios.

The market share of catches by trawlers and coastal vessels is also affected by the change in population dynamics. Trawl catches are initially more than twice those of coastal vessels. By the end of the simulation, the relative share of landings by coastal vessels increases in all scenarios. The extent to which the gap closes between the amounts caught by the two vessel types is particularly pronounced in the scenarios with large changes in population dynamics.

The overall trajectory of capelin catches is also negative (Table 2). However, the long-term impact is less extensive than for the cod catches, owing to the speedier adjustment of capelin to the new population dynamics, to reduced cod stock size, and the subsequent release of predation pressure.

The net present value of discounted profits in the period 50−64 years changes only very little despite considerable adjustments in stock sizes and landings caused by the changes in population dynamics (Table 3). As the large differences in economic returns from fishing only start about 5 years after the change in population dynamics, the significant economic consequences are partly hidden by discounting.

The long-term economic consequences of a reduction in productivity are more pronounced (Table 3). Cod fishing fleets suffer considerable reductions in profits. In all scenarios, the trawl fishery is hit hardest because of the high operational costs. Coastal vessel profits also become negative for large reductions in the productivity. In contrast, the capelin fishery is affected to a lesser extent. One reason is the less drastic decline in stock size caused by the change in population dynamics. Another reason is that the capelin stock and catches are higher around year 70 and lower at year 84, whereas the situation is opposite for cod as a consequence of discounting. The particularly bad years of the cod fishery are emphasized, while they receive less attention in the capelin fishery because they are near the end of the period of interest. However, the overall negative trajectories for all fisheries caused by reductions in productivity remain evident in all scenarios despite the influence of discounting.

Decrease in environmental carrying capacities

A reduction in the environmental carrying capacity of both fish species has an effect on the stocks similar to that of a reduction in the productivity. The cod stock, with an average stock size of roughly 2 million tonnes in the reference scenario, is heavily impacted. The initial decline in stock size after the reduction of the carrying capacity is particularly pronounced (Figure 3). If the carrying capacity is reduced by 50%, cod biomass shrinks to less than 700 000 t. On the other hand, cod can recover in subsequent years in all scenarios. After such a slight recovery, cod biomass stabilizes at a level of more than 1 million tonnes. A decline in the carrying capacity leads to a longer periodicity of fluctuation of cod, which increases from 20 to almost 30 years between two peaks.

The impact of reduced carrying capacity on the capelin stock trajectory is less. With the stock biomass already

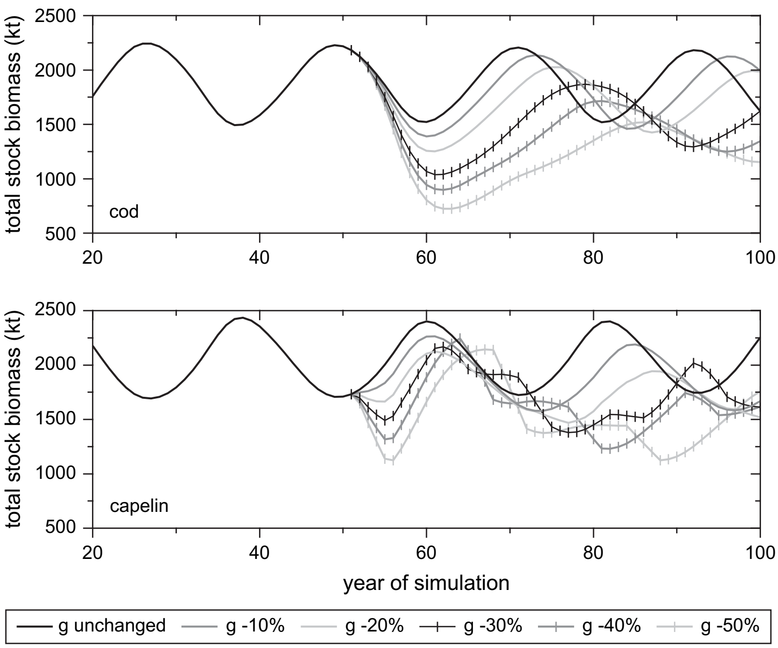

Figure 2. Stock size trajectories for cod and capelin with reduced productivity.

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Table 2. Annual catch trajectories when productivity is reduced.

Time period, change in productivity	Trawlers (cod) Average annual catch ('000 t)	Trawlers (cod) Change from reference scenario (%)	Coastal vessels (cod) Average annual catch ('000 t)	Coastal vessels (cod) Change from reference scenario (%)	Purse-seiners (capelin) Average annual catch ('000 t)	Purse-seiners (capelin) Change from reference scenario (%)
Years 30–44	168.7		74.1		1 022.3	
Years 50–64						
Reference scenario	164.7		98.1		977.5	
g −10%	157.1	−4.6	94.6	−3.6	938.9	−3.9
g −20%	149.4	−9.3	91.0	−7.2	894.1	−8.5
g −30%	150.6	−8.6	85.2	−13.1	842.3	−13.8
g −40%	142.2	−13.7	81.8	−16.6	692.4	−29.2
g −50%	132.4	−19.6	81.8	−16.6	637.3	−34.8
Years 70–84						
Reference scenario	150.8		123.1		949.0	
g −10%	126.1	−16.4	108.6	−11.8	810.2	−14.6
g −20%	93.4	−38.1	85.2	−30.8	682.7	−28.1
g −30%	67.4	−55.3	42.1	−65.8	588.0	−38.0
g −40%	40.0	−73.5	28.4	−76.9	524.1	−44.8
g −50%	24.3	−83.9	19.5	−84.2	486.2	−48.8

fluctuating substantially in the reference scenario, only a reduction of the carrying capacity by 30% or more causes the stock size to clearly deviate downwards from the original range of fluctuation (Figure 3). The reduction of the carrying capacity causes an initial decline of the stock, compared with the increase in the reference scenario. Subsequently, there is a rise in biomass that can be attributed mainly to the concurrent strong decline of the cod stock. This causes much smaller losses of capelin through predation by cod. A consequence of the reduced predation pressure is the marked increase in capelin stock biomass only a few years after the first breakdown of the population size.

Reduction in the environmental carrying capacity of cod severely affects the amount of cod harvested. In the long term, average annual landings by trawlers and coastal vessels both decrease by up to 75% (Table 4). However, the change in the carrying capacity leads to an increase in the harvest by trawlers during the first few years following the change of the carrying capacity. The greater the reduction in carrying capacity, the longer the time after year 50 in which the fishing effort by trawlers remains elevated. Consequently, average annual catches remain quite stable in all scenarios during the first decade after the change in carrying capacity, and are only slightly lower than in the reference scenario. On the other hand, the greater the effort to maintain large harvests, the more severe will be the long-term reduction in landings. Cod catches by both vessel types subsequently decline by up to 75% within only a few years, before stabilizing at a greatly reduced level, with total annual cod catches in some cases remaining below 100 000 t.

In contrast, catches of capelin are less influenced by a change in the carrying capacity than by a reduction in productivity. For slight declines in carrying capacity, average capelin landings during the first decade remain practically unchanged (Table 4).

Table 3. Trajectories of net present value of profits when productivity is reduced.

Time period, change in productivity	Net present value of profits (million Nkr) Trawlers (cod)	Coastal vessels (cod)	Purse-seiners (capelin)
Years 30–44	581.9	413.4	695.1
Years 50–64			
Reference scenario	212.8	448.9	616.7
g −10%	211.4	448.4	614.8
g −20%	209.9	447.8	612.8
g −30%	208.6	447.1	610.7
g −40%	206.9	446.4	608.7
g −50%	205.0	445.7	606.8
Years 70–84			
Reference scenario	−199.8	577.3	613.4
g −10%	−677.3	182.9	590.0
g −20%	−959.6	−115.2	586.8
g −30%	−998.4	−252.1	498.5
g −40%	−1107.3	−315.3	535.8
g −50%	−1198.4	−335.9	611.2

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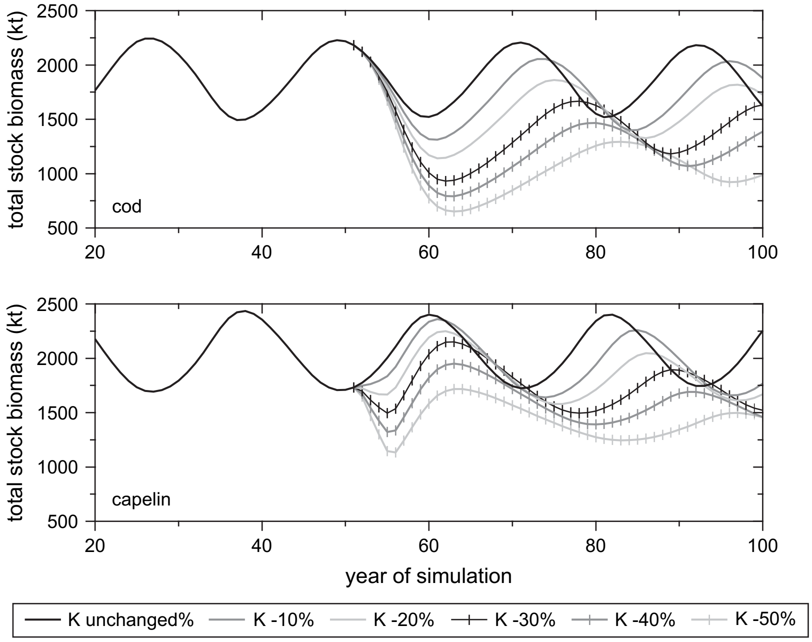

Figure 3. Stock size trajectories for cod and capelin with reduced carrying capacities.

Compared with the reference scenario, average annual harvests remain fairly stable in the long term, with average harvests still totalling more than 70% of the original value, even for a large reduction in carrying capacity.

Reducing environmental carrying capacities has no negative short-term economic impact. The net present value of profits from fishing for all vessel types remains unchanged (Table 5). This is primarily because of the

Table 4. Annual catch trajectories when the environmental carrying capacity is reduced.

	Trawlers (cod)		Coastal vessels (cod)		Purse-seiners (capelin)	
Time period, change in carrying capacity	Average annual catch ('000 t)	Change from reference scenario (%)	Average annual catch ('000 t)	Change from reference scenario (%)	Average annual catch ('000 t)	Change from reference scenario (%)
Years 30–44	168.7		74.1		1 022.3	
Years 50–64						
Reference scenario	164.7		98.1		977.5	
K −10%	167.8	+1.9	91.8	−6.4	966.4	−1.1
K −20%	157.8	−4.2	93.6	−4.6	928.1	−5.1
K −30%	156.9	−4.7	87.6	−10.7	888.8	−9.1
K −40%	147.2	−10.6	83.9	−14.5	821.7	−15.9
K −50%	137.6	−16.5	80.1	−18.3	745.7	−23.7
Years 70–84						
Reference scenario	150.8		123.1		949.0	
K −10%	148.6	−1.5	84.9	−31.0	848.3	−10.6
K −20%	100.3	−33.5	89.8	−27.1	792.1	−16.5
K −30%	84.3	−44.1	50.9	−58.7	753.8	−20.6
K −40%	54.7	−63.7	39.1	−68.2	720.5	−24.1
K −50%	32.6	−78.4	22.4	−81.8	679.5	−28.4

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increased fishing effort on cod, keeping cod landings at high levels for up to four years longer than in the reference scenario. The depletion of the cod stock caused by this fishing behaviour leads to significantly reduced predation on capelin. More capelin remains available for harvesting, which increases annual profits in the capelin fishery.

The long-term impacts of the change in environmental carrying capacity are bleak for the cod fishery (Table 5). Whereas coastal vessels remain profitable if the carrying capacity of cod is reduced only a little, the cod fishery is unprofitable for trawlers after a substantial decline in the carrying capacity. In the long term, the capelin fishery can even profit from a change in population dynamics: the net present value of profits is higher than in the reference scenario if cod reduction has occurred to allow less predation, leading to a larger capelin biomass and therefore larger harvests.

Combination of both effects

In this experiment, we explored the possibility that a change in environmental conditions causes both productivities and environmental carrying capacities to be affected at the same time, so changes in population dynamics were combined to assess how a simultaneous change of these quantities affects economic returns to the cod and capelin fisheries.

Results show that profits from fishing are only marginally affected when both changes in population dynamics occur concurrently. For a given change in the carrying capacities, a larger decrease in the productivity has only a small additional effect on the net present value of profits.

Table 5. Trajectories of net present value of profits when the environmental carrying capacity is reduced.

Time period, change in carrying capacity	Net present value of profits (million Nkr)		
	Trawlers (cod)	Coastal vessels (cod)	Purse-seiners (capelin)
Years 30–44	581.9	413.4	695.1
Years 50–64			
Reference scenario	212.8	448.9	616.7
K −10%	211.9	448.4	614.8
K −20%	210.3	447.9	612.8
K −30%	208.8	447.2	610.8
K −40%	207.0	446.5	608.8
K −50%	205.1	445.7	606.7
Years 70–84			
Reference scenario	−199.8	577.3	613.4
K −10%	−547.5	11.5	642.6
K −20%	−899.4	−84.9	684.2
K −30%	−962.9	−245.6	739.3
K −40%	−1079.3	−312.1	718.4
K −50%	−1189.6	−375.9	672.6

Considering the period immediately following the change in population dynamics, discounted profits are similar for a given change in carrying capacity, regardless of the extent of the change in productivity. The impact of the increase in trawler effort to stabilize profits despite decreasing cod carrying capacity can be observed in all scenarios, regardless of the magnitude of an additional change in cod productivity. In the long term, however, a combination of reductions in productivity and carrying capacity of the two species causes the cod fisheries of both fleets to become unprofitable while profits of the purse-seine fishery for capelin remain positive for the remainder of the simulations.

The influence of the share of capelin devoted to human consumption

Traditionally, most Norwegian capelin catches are used to produce fishmeal and fish oil. In recent years, there has been an increase in the amount of capelin exported and used for human consumption. Some 50% of the capelin landed by Norway were exported in 1999 (Statistisk Sentralbyrå, 2002), the market price being up to seven times as high as the price for capelin used industrially in Norway (Fiskeridirektoratet, 2001).

In a sensitivity analysis, the share of capelin used for human consumption was set to different levels between 0% and 50%, the market price of capelin being increased with more used for export. We assume that capelin market price used industrially $P_{\mathrm{cap,ind}}$ is 0.60 Norwegian kroner (crowns; Nkr) per kg while the capelin market price used for consumption $P_{\mathrm{cap,hum}}$ is Nkr 4.20 per kg, so the average price level of capelin in the simulations turns out to be between Nkr 0.60 and Nkr 2.40 per kg.

Simulations with different capelin price levels show that the quantity of capelin caught in each fishing period does not change despite the increased value of the resource. This is because in all scenarios, the catch by purse-seiners is so high as to leave little room for fishing effort to expand. However, the net present values of profits of the capelin fishery increase substantially (Table 6) for a higher average price of capelin during all time periods of the simulations. If an average of just 10% of the capelin is used for human consumption, the net present values of profits are almost doubled. By contrast, the cod fishery remains virtually unaffected by changes in the price of capelin, because landings and profits from fishing remain practically unchanged.

The influence of the discount rate

All simulations described have been conducted with a discount rate of 7%. In order to determine the influence of the discount rate on profits, simulations relative to the reference scenario are conducted with discount rates ranging from 1% to 15%. In this sensitivity analysis, there is no change in population dynamics, to ensure comparability between the

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Table 6. Trajectories of net present value of profits in the capelin fishery when the capelin average market price increases.

Average market price of capelin (Nkr per kg)	Net present value of profits (million Nkr)		
	Years 30−44	Years 50−64	Years 70−84
0.60	695.1	616.7	613.4
0.96	1 180.5	1 055.2	1 049.9
1.32	1 666.0	1 493.7	1 486.4
1.68	2 151.4	1 932.1	1 922.9
2.04	2 636.9	2 370.6	2 359.4
2.40	3 122.3	2 809.1	2 795.9

scenarios. Net present values of profits are calculated for the three time periods of interest. Results indicate that the relationship between the net present value of profits and the interest rate is similar in all three periods, so the assessment of the time period between years 30 and 44 can be used as an example for all three periods of interest.

Results show that discount rates have a profound impact on the net present value of profits, which are affected differently depending on fleet type. Low discount rates lead to the worst overall net present value, which is negative because of losses made by both trawlers and coastal vessels (Table 7). High discount rates only favour the net present value of profits of capelin fishing fleets, whereas the economic results of cod fishing fleets diminish. Overall, the net present value of profits is greatest at moderate discount rates between 7% and 11%, when the economic results of all fishing fleets are distinctly positive.

In general, the trend is the same for both cod fleets. The scheme is different for the capelin purse-seine fleet. The size of the capelin stock and therefore the landings fluctuate more than the cod stock and cod catches. Consequently, the profitability of the capelin fishery tends to increase with higher discount rates, because good fishing years at the beginning of the period of interest are offset to a lesser degree by worse harvests just a few fishing periods later.

Table 7. Influence of the discount rate on fishing profits.

Discount rate (%)	Net present value of profits (million Nkr)		
	Trawlers (cod)	Coastal vessels (cod)	Purse-seiners (capelin)
1	−816.5	−192.9	104.0
3	−376.3	152.9	282.7
5	208.7	298.6	511.1
7	581.9	413.4	695.1
9	711.2	413.9	833.4
11	593.1	458.6	1 053.0
13	458.9	247.2	1 246.3
15	−98.4	46.0	1 397.8

The influence of the learning factor

We examined the importance of the speed at which fishers adjust their harvest strategies. Even without changes in the population dynamics, the economic result of a fishing fleet changes depending on the speed at which fishers utilize new information about the trends in fish stock sizes.

A learning factor of 0.5 in the simulations leads to a solid overall economic result, with similar net present values of profits for all fleet types. However, considering the net present value of profits from fishing during years 50−64, which is representative of all three periods of interest, none of the fleets obtain the best economic result at such a speed of strategy adjustment. For purse-seiners, it is advantageous to utilize information on the population dynamics of the capelin stock as fast as possible (Table 8), even though differences between the returns from fishing vary little with learning factor.

Relying only on the long-term trajectory of the cod stock leads to very bad economic results that might even include losses (Table 8). For cod fishers, it is best to utilize much of the newly gained information, i.e. to place greater weight on the real stock trajectory than on the previously applied expected stock growth rates when updating the expected productivity. The best economic result for trawlers is achieved with learning factors of 0.8 or 0.9. However, for coastal vessels, which target slightly older age classes than trawlers, the importance of previous experience of fishers is greater. Their best economic results are obtained for learning factors between 0.3 and 0.4.

Discussion and conclusions

Simulations reveal that adverse changes in fish population dynamics can have long-term negative impacts on the stock sizes of the fish species assessed. Reducing productivity or environmental carrying capacity leads to smaller stock sizes, which will cause landings to decrease. Results for the cod stock show that the decline in stock size is slightly greater when the carrying capacity is affected than when the productivity changes.

Capelin decline less than cod. The extent of the decline is about the same for both types of change in population dynamics. That the decline in capelin is not greater for a reduction in the carrying capacity can be attributed to the interaction between the two species in the simulation model. When the carrying capacities of the two species are reduced, the cod stock is significantly affected, causing a release in predation pressure. To a large part, this offsets the initial effect of changed carrying capacity on the capelin stock.

The reduced landings of both species negatively affect fisheries economics. However, the net present value of profits between years 50 and 64 veils the extent of the

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Table 8. Influence of the learning factor on fishing profits.

Learning factor	Net present value of profits (million Nkr)		
	Trawlers (cod)	Coastal vessels (cod)	Purse-seiners (capelin)
0.1	−414.5	62.1	725.0
0.2	−343.8	118.9	658.4
0.3	−86.7	670.5	619.3
0.4	−86.7	670.5	619.3
0.5	212.8	448.9	616.7
0.6	212.8	448.7	616.7
0.7	212.8	448.7	616.7
0.8	415.0	532.9	685.5
0.9	329.3	685.9	725.0

long-term impacts of changes in population dynamics. Discounting causes years with high catches at the beginning of a 15-year period to be more important than years with lower catches at the end of the same time period. Consequently, the net present value of profits of this time period remains unchanged.

Interestingly, an increase in fishing activity during the sixth decade of the simulation despite a reduced carrying capacity is hidden by the stable net present value of profits. The greater the change in population dynamics, the more the fishing effort is increased to maintain the high level of catches. Increased fleet utilization results in short-term economic gain, so returns remain at the same level as in the reference scenario. The strategy to increase fleet utilization to preserve large landings is rather short-sighted. Catch sizes and profits can be kept stable at a high level for just a few years longer with reduced stock size. However, this exploitation scheme causes such great harm to the cod stock that a recovery of the stock in later years is practically impossible.

The long-term negative trend in catch size caused by changes in population dynamics and the subsequent diminishing economic returns is clearly evident. The net present value of profits during years 70 through 84 shows that the more valuable cod fishery is more affected by negative stock size trajectories than the capelin fishery. The cost-intensive operation of large trawlers requires that annual landings do not drop considerably below current levels. In many scenarios, the cod trawler fishery becomes unprofitable if stock sizes decline such that the initial harvests can no longer be sustained.

A comparison of the simulation results with ICES stock assessment data shows that the average stock size of cod in the model and the calculated trawler and coastal vessel catches prior to the change in population dynamics agree relatively well with the official statistics. Currently, the cod stock in the Barents Sea has a biomass (age 3 and older) of about 1.5 million tonnes and cod landings total roughly 450 000 t, most of which is caught by trawlers (ICES, 2003a; Michalsen, 2004). In the simulations, the cod stock biomass averages about 1.9 million tonnes in the reference scenario and annual harvests amount to around 250 000 t. In contrast, there are larger discrepancies between model results and observed values for the capelin stock and the quantity of capelin harvested. The model generally overestimates capelin stock size, which causes the purse-seine catch of capelin and the subsequent economic result for this fishery to be too high. A possible reason for this discrepancy between model and reality is that the model only considers the predator−prey relationship between cod and capelin, neglecting interactions of capelin with other species in the ecosystem.

It is possible that the quality of simulation results of capelin stock size can be improved if herring is considered as a third species in the model. Young herring feed extensively on capelin larvae. If large year classes of young herring are present in the Barents Sea, their predation on capelin larvae can severely impact capelin recruitment success (Gjøsæter and Bogstad, 1998). The consequence would be a significantly reduced capelin stock that can only rebuild when the young herring have left the Barents Sea to join the adult herring stock in the Norwegian Sea. Even though large year classes of young herring are found in the Barents Sea infrequently, their predation leads to a smaller adult stock of capelin and increased variability in the capelin biomass in subsequent years.

Another difficult aspect of the model set-up is to represent the harvest strategies of the fishers in a realistic manner. In this model version, the harvest strategies are not based on rational behaviour that only considers maximization of profits over a certain time period as the sole basis of decision-making, but on adaptation. Adaptation of harvest strategies is characterized by the adjustment of fleet utilization based on a comparison of the catch size with a previously calculated target value. As the criteria for adjusting fishing effort do not depend on the profit from fishing in the fishing period in question, but rather on the proximity to the target value, the profits from fishing obtained by following this strategy are obviously smaller than profits that would have been obtained if profit-maximizing harvesting strategies had been addressed.

Adaptive harvesting strategies were used in this model because they have the advantage that the size of the fish stock and the expected recruitment success are considered when fishing effort is determined. Logistic stock growth functions were used in the calculation of target catch sizes instead of the data on the age structure and recruitment to the stocks from the biological module of this model. This way the calculations can be readily carried out, relying only on a limited number of key parameters underlying stock size trajectories. As the determination of harvesting strategies and the calculations involving the population dynamics of the two species are conducted independently,

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no problems arise from the use of two different underlying biological models in the two contexts. This set-up actually allows the assessment of different harvesting strategies of varying complexity without changing the update rules used to describe the stock trajectories.

In the long term, adaptive harvesting strategies seem more sustainable than profit-maximizing strategies, despite the fact that profits from fishing never reach the maximum possible value. However, simulation results with a reduced environmental carrying capacity of cod show that even adaptive harvesting strategies can be detrimental to a stock size trajectory. This holds particularly in cases in which restrictions to the adaptation rule cause the adjustment of fishing effort to be too slow to ensure sustainable management of the fish stock.

Despite these caveats, it is possible to use this simulation model to obtain some preliminary insights into the possible consequences of a reducing productivity and/or environmental carrying capacity on cod and capelin stocks in the Barents Sea and the catches of their fisheries. The model will now be further developed in order to obtain a more differentiated image of the economic consequences caused by a sudden change of the population dynamics of the exploited fish stocks. This will enable us to analyse particular scenarios that arise from changes in climatic or hydrographic conditions.

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Appendix 1

List of the symbols used in the model

Symbol	Meaning
a	Index denoting the age class
A	Oldest age class of a species
B	Biomass
cap	Index referring to capelin
cod	Index referring to cod
D	Prey density
e	Fleet utilization
g	Reproduction-induced productivity
G	Expected growth of the stock
h	Harvest
harv	Index denoting the stock size after harvesting has been considered
hum	Index referring to human consumption
i	Index denoting fleet type
ind	Index referring to industrial use
init	Index referring to the beginning of a fishing period
K	Carrying capacity
n	Number of individuals in an age class
P	Fish price
pred	Index denoting the stock size after harvesting and predation have been considered
q	Catchability coefficient
r	Revenue
R	Recruitment
s	Index denoting species
SSB	Spawning-stock biomass
sw	Spawning weight
t	Index denoting fishing period
v	Number of vessels
w	Weight
α	Parameter used in the recruitment function
β	Parameter used in the recruitment function
δ	Discount factor
θ	Variable costs
Θ	Cost per unit effort
κ_1	Rate of predation
κ_2	Parameter used in calculation of predated biomass
λ	Learning factor
μ	Proportion of individuals mature
π	Profit per fishing period
Π	Net present value of profits over a 15-year period
φ	Fixed costs
χ	Natural survival rate
ψ	Total costs

Appendix 2

Parameters and initial values used in the simulations

Parameter	Value	Source
Population dynamics of capelin		
Initial number of individuals in each age group $n_{\mathrm{cap},a,0}$	[2.16e + 11 1.70e + 11 5.64e + 10 9.97e + 09 0.73e + 09]	Based on ICES (2003b)
Mean weight in each age group $w_{\mathrm{cap},a}$	[0.0036 0.0102 0.0182 0.024 0.0265] kg	Based on ICES (2003b)
Proportion of individuals mature $\mu_{\mathrm{cap},a}$	[0.00 0.01 0.41 0.87 1.00]	Based on ICES (1999)
Mean spawning weight per age class $\mathrm{sw}_{\mathrm{cap},a}$	[0.00324 0.00918 0.01638 0.0216 0.02385] kg	Calculated from mean weight-at-age
Natural rate of survival χ_{cap}	0.535	Eide and Flaaten (1994)
Initial value for productivity $g_{\mathrm{cap},0}$	0.5	
Initial value for carrying capacity $K_{\mathrm{cap},0}$	10 million tonnes	
Initial value of recruitment parameter $\alpha_{\mathrm{cap},0}$	4 491	Set to be consistent with initial carrying capacity
Initial value of recruitment parameter $\beta_{\mathrm{cap},0}$	9	Set to be consistent with initial carrying capacity
Population dynamics of cod		
Initial number of individuals in each age group $n_{\mathrm{cod},a,0}$	[9.82e + 08 2.91e + 08 1.78e + 08 1.17e + 08 7.31e + 07 3.59e + 07 1.25e + 07 3.4e + 06 8.0e + 05 4.0e + 05 2.6e + 05 1.12e + 05 4.8e + 04 2.1e + 04 9.0e + 03]	Based on ICES (2003a)
Mean weight in each age group $w_{\mathrm{cod},a,0}$	[0.104 0.42 0.85 1.30 1.89 2.73 3.87 5.28 6.87 8.33 10.10 12.36 12.72 13.60 16.71] kg	Based on ICES (2003a)
Proportion of individuals mature $\mu_{\mathrm{cod},a}$	[0 0 0.02 0.023 0.08 0.315 0.591 0.787 0.891 0.973 0.99 1.0 1.0 1.0 1.0]	Based on ICES (2003a)
Mean spawning weight per age class $\mathrm{sw}_{\mathrm{cod},a,0}$	[0.094 0.378 0.765 1.170 1.701 2.457 3.483 4.572 6.183 7.497 9.090 11.124 11.448 12.240 15.039] kg	Calculated from mean weight-at-age
Natural rate of survival χ_{cod}	0.8	Sumaila (1995)
Initial value for productivity $g_{\mathrm{cod},0}$	0.5	Eide (1997)
Initial value for carrying capacity $K_{\mathrm{cod},0}$	6 million tonnes	Sumaila (1995)
Initial value of recruitment parameter $\alpha_{\mathrm{cod},0}$	682	Set to be consistent with initial carrying capacity
Initial value of recruitment parameter $\beta_{\mathrm{cod},0}$	1.5	Set to be consistent with initial carrying capacity
Parameters relating to the predator–prey relationship		
Maximum value of $D_{\mathrm{cap},t}$: $D_{\mathrm{cap,max}}$	1.5	Moxnes (1992)
Standard biomass of capelin $B_{\mathrm{cap,std}}$	4.467 million tonnes	Moxnes (1992)
Rate of weight increase of cod $\hat{w}_{\mathrm{cod},a}$	[0.25 0.33 0.35 0.46 0.65 0.88 1.09 1.23 1.13 1.37 1.75 0.28 0.68 2.41 0.10] kg	Set to be consistent with initial values of weight-at-age data
Rate of predation κ_1	1.235	Moxnes (1992)
Influence of predation on weight of cod κ_2	0.6	Moxnes (1992)
Economic parameters of trawlers		
Fleet size v_{TR}	60	Adapted from Statistisk Sentralbyrå (2002)
Catchability coefficient q_{TR}	0.0074	Sumaila (1995)
Fixed costs φ_{TR}	Nkr 15.12 million	Sumaila (1995)
Variable costs θ_{TR}	Nkr 12.88 million	Sumaila (1995)
Economic parameters of coastal vessels		
Fleet size v_{CV}	500	Adapted from Statistisk Sentralbyrå (2002)
Catchability coefficient q_{CV}	0.00593	Sumaila (1995)
Fixed costs φ_{CV}	Nkr 0.65 million	Sumaila (1995)
Variable costs θ_{CV}	Nkr 0.88 million	Sumaila (1995)

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Appendix 2 (*continued*)

Parameter	Value	Source
Economic parameters of purse-seiners		
Fleet size v_{RW}	70	Adapted from Statistisk Sentralbyrå (2002)
Catchability coefficient q_{RW}	0.0175	Adapted from Sumaila (1997)
Fixed costs φ_{RW}	Nkr 0.42 million	Adapted from Sumaila (1997)
Variable costs θ_{RW}	Nkr 0.58 million	Adapted from Sumaila (1997)
General economic parameters		
Discount factor δ	0.07	Sumaila (1995)
Market price of capelin that is used industrially $P_{cap,ind}$	Nkr 0.60 per kg	Based on Fiskeridirektoratet (2001)
Market price of capelin that is used for consumption $P_{cap,hum}$	Nkr 4.20 per kg	Based on Fiskeridirektoratet (2001)
Market price of cod P_{cod}	Nkr 6.78 per kg	Sumaila (1995)
Learning factor λ_s	0.5 for all fleets	

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