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

Working Paper FNU-30

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Abstract

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 an external reduction of the reproductive rates and/or the carrying capacities. The 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 both lead to lower stock levels and consequently to smaller catch sizes. There is only a small short-term economic impact on the fisheries but the long-term consequences are quite pronounced. In some cases, a higher fishing activity in the first few years after the change in population dynamics causes harvest sizes to remain stable despite diminishing stock sizes. This stabilizes the returns from fishing in the short run but veils the apparent negative long-term impact on the fisheries resulting from adversely affected stock dynamics.

Key Words: Barents Sea, bioeconomic modeling, capelin, cod, population dynamics

1 Introduction

The size and the range of fish stocks depend on the existing hydrographic conditions. Changes in temperature, salinity or oxygen content can have adverse effects on the population dynamics of fish stocks, sometimes even causing the stocks to collapse, especially when they are subject to fishing activities by humans. 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 models currently used for the assessment of 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 changes in hydrographic conditions such as shifts initiated by e.g. a weakening of the thermohaline circulation (THC), since they are normally used for short-term predictions of the development of the stocks.

Studies of stock development 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 due to a weaker THC would therefore adversely affect recruitment success and thus the overall development of Barents Sea cod. The capelin (*Mallotus villosus*) stock would be similarly affected by such a change in the Barents Sea temperature regime, since reduced food availability would negatively influence the growth of the individual capelin and the overall stock size (Skjoldal *et al*., 1992). Such reductions of the stock sizes inevitably have an effect on the fisheries of these species.

This study assesses the economic impacts that a sudden change in the fish population dynamics would have using a bioeconomic simulation model, 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 reproduction and the environmental carrying capacity. Cod and capelin fisheries were selected because the cod fishery is of great economic importance in Norway. Capelin is one of the main food sources of cod. Therefore, changes in the Barents Sea capelin stock size will have an effect on the cod stock as well. In the following, 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 in the subsequent section. Results of the simulations with the model are given in section four. Section five discusses the consequences that a severe change in fish population dynamics would have on the fisheries of the Arcto-Norwegian cod and Barents Sea capelin stocks.

2 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 important fish stocks for commercial exploitation worldwide (Sumaila, 1995). Cod mainly prey on capelin, herring (*Clupea harengus*), haddock (*Melanogrammus aeglefinus*), young individuals of its own species as well as shrimp (*Pandalus borealis*) and other invertebrates (Mehl, 1989).

In the past, the size of the Arcto-Norwegian cod stock has shown significant variability. Overall, total biomass declined from more than 3 million tons in the 1950s to roughly one million tons in the 1980s due to an increase in fishing activity (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 over 2 million tons in the early 1990s.

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

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

Annual catches of Barents Sea capelin amounted to more than one million tons during the stable period of capelin stock size until the mid-1980s. Then the stock collapsed within two years which forced a 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 until 1998. The subsequent increase in stock size was rather short-lived so that harvesting of Barents Sea capelin could only occur for a few years. When the stock decreased in recent years, it was necessary to close the fishery once more since 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 tons is 95% (Commission of the European Communities, 2005). Because of the substantial capelin stock dynamics the capelin TAC based on this 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 of Arcto-Norwegian cod was set to 486 000 and 485 000 tons, respectively (Michalsen, 2004; Commission of the European Communities, 2005). Due to the poor current state of the capelin stock, both countries agreed to refrain from fishing capelin in 2004 and 2005.

Bioeconomic modeling of the Barents Sea fisheries

Modeling studies of the Barents Sea fisheries have focused on both the biological and economic consequences of different management strategies or different economic regimes. The single-species model CAPELIN was a first attempt to simulate the development of the capelin stock size (Tjelmeland, 1985) which was used to determine the harvest that would lead to an optimal further development of the stock. However, the focus on a single fish species has the disadvantage that species interactions are neglected. The model BIFROST (Gjøsæter *et al.*, 2002) was used to assess the short-term development 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 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 of the cod and capelin fisheries in the Barents Sea. He showed that the consideration of 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 that is necessary to optimally exploit the cod stock. The application of an expanded version including the 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 an uncoordinated and competitive exploitation (Sumaila, 1997).

Eide (1997) and Armstrong and Sumaila (2000) analyzed 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). The present share of the cod trawlers should be reduced in favor of the smaller coastal vessels since those generally target older cod age classes than do the trawlers (Armstrong and Sumaila, 2000) which would lead to an improvement of the economic results in the long run.

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 (ITQ). They showed that an ITQ introduction would not result in a significant improvement of the economic output due to possible negative effects arising from one fleet type buying up all quotas.

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

3 Methods

The simulation model

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

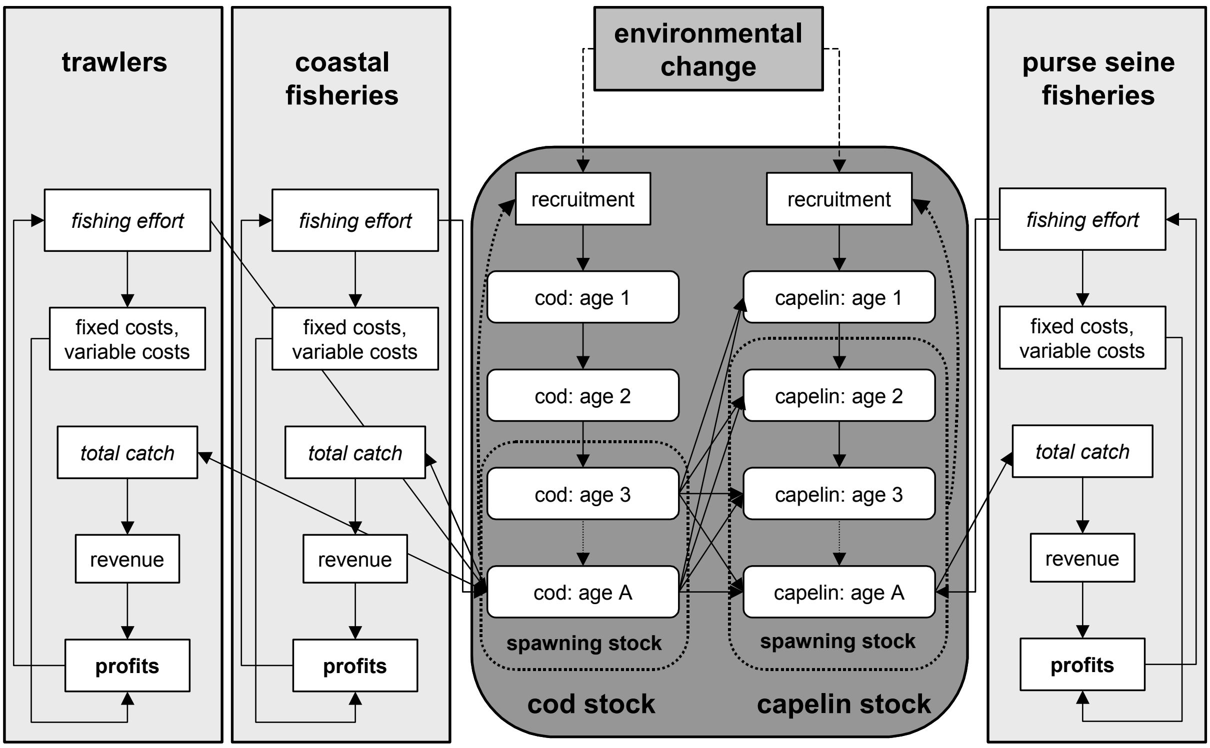

Figure 1. Structure of the simulation model.

The model covers two important fish species of the Barents Sea that are harvested commercially, cod and capelin (Fig. 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 vessels. Other means of catching capelin are of little importance and therefore neglected.

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.

population dynamics of the fish species

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

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

$$(3)\quad SSB_{s,t} = \sum_a \mu_{s,a} sw_{s,a} n^{harv}_{s,a,t}$$

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

$$n^{init}_{s,1,t+1} = R_{s,t}$$

$$(5)\quad n^{init}_{s,a+1,t+1} = \chi_{s,a} n^{harv/pred}_{s,a,t}$$

$$n^{init}_{cod,A,t+1} = \chi_{cod,A} n^{harv}_{cod,A,t} + \chi_{cod,A-1} n^{harv}_{cod,A-1,t}$$

exploitation of the stocks

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

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

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

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

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

predation and weight increase

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

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

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

adaptive harvesting strategies

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

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

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

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

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

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

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

The time horizon is one century. Each fishing period has lasts one year. Stock size changes in each fishing period due to harvesting, natural mortality, predation and recruitment. During the simulation, a change of the reproductive rate and/or the carrying capacity takes place, forcing a change in recruitment and thus in the long-term development of the stock. 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 reproductive rates 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 development 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 5 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 (Eq. 1). Stock size is reduced by harvesting of the various fishing fleets (Eq. 2). Stocks interact via predation (Eqs. 6 & 7) with the rate of cod weight increase depending on the extent of capelin consumption (Eq. 8, cf. Magnússon and Pálsson, 1991). The average capelin weight-at-age is assumed constant.

Recruitment depends on the stock size at the end of the harvesting period (Eq. 3). The number of recruits (Eq. 4) is obtained using a Beverton-Holt recruitment model (Beverton and Holt, 1954) where the parameters are set such that the equilibrium biomass of unexploited stocks in the reference scenario would be 6 million tons for cod (Sumaila, 1997) and 10 million tons 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 (Eq. 5).

The fisheries

All fleets engage in harvesting activities during each fishing period (Eq. 9). It is assumed that the demand curve is perfectly elastic, i.e. the market price of both species remains constant regardless of the quantities landed. Some capelin is sold for human consumption at a higher price while most of the catch is used for the production of fish meal and oil; we use a weighted average that is slightly above the capelin price for industrial use.

Profits of each fleet (Eq. 12) reflect differences between revenues from sales of landings (Eq. 10) and the total cost of fleet operation consisting of fixed costs for fleet maintenance which are independent of fleet utilization and variable costs directly related to the extent of fleet utilization (Eq. 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 time period before the change in population dynamics), 50-64 years (i.e. the time period revealing short-term impacts of the change in population dynamics), and 70-84 years (i.e. a time period in which long-term impacts of changes in population dynamics become evident). Profits are discounted at rate δ (Eq. 13). The control variable is the fishing effort. The boundary condition for the economic exploitation of fish stocks are the population dynamics of the two species.

The harvesting strategy of the fishermen

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

The expected reproductive rate of the fish stock, which is important for the calculation of the target value of catches, is also updated. This is done on the basis of the actually observed development of stock sizes (Eq.18) which is used in a learning function (Eq. 19) to determine a weighted average of the actual and previously expected rates of reproduction. This weighted average is then used as a basis for the above calculations in the next fishing period.

4 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 of the rates of reproduction 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 from 1983 to 2002 for cod (ICES, 2003a) and capelin (ICES, 2003b). An overview of the parameters used in the simulations is given in Appendix B.

Reduction of the rates of reproduction

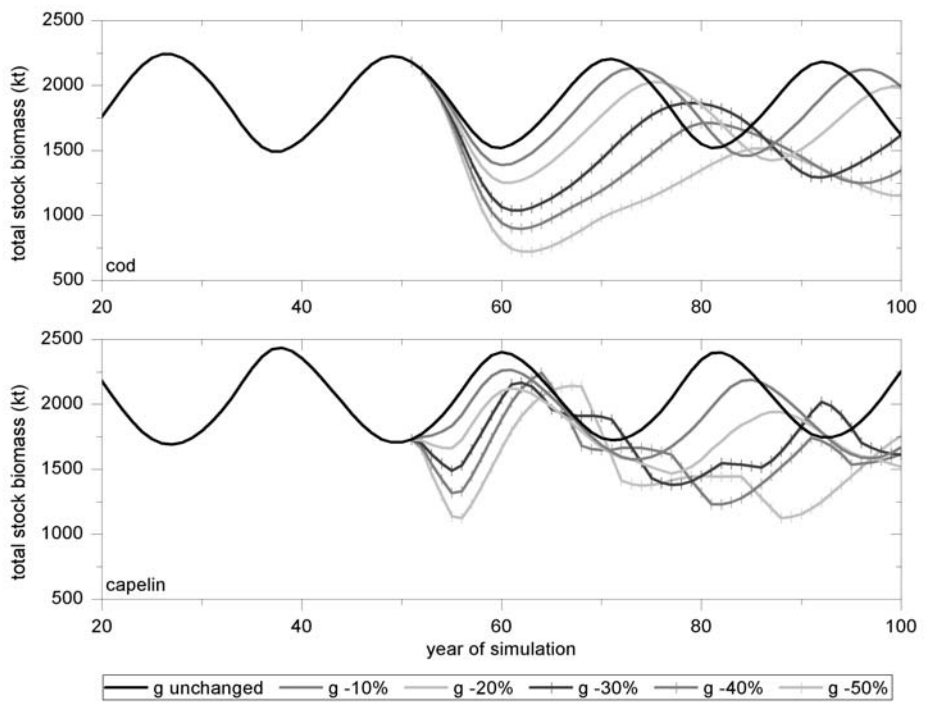

Figure 2. Development of the stock sizes with reduced rates of reproduction.

A decline in the rates of cod and capelin reproduction leads to smaller stock sizes. The cod stock decreases by roughly one third for a reduction of the reproductive rate by 50% (Fig. 2). The periodicity of the fluctuation of the stock size, which is the consequence of the rule of updating the fishing effort of the fleets, increases substantially with a smaller total stock biomass. The development of the capelin stock follows the same general pattern. In the reference scenario, the overall capelin stock biomass fluctuates around an average value of approximately 2 million tons. Reducing the rate of reproduction by 50% decreases the average stock size to roughly 1.5 million tons. The impact of the change of the capelin reproductive rate on the stock size becomes evident earlier than the reduction of the cod stock size owing to the much shorter life-span 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.

time period	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
change of the rate of reproduction	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
years 30-44	168.7		74.1		1022.3	
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%

Table 2. Development of annual catches when the rate of reproduction is reduced.

Because of the reduced stock sizes, annual cod and capelin catches decline in size. Compared to the reference scenario, in which annual trawl catches of cod fluctuate around 160 000 tons and annual coastal vessel catches total slightly less than 100 000 tons per year (Tab. 2), catches decline notably even for small reductions of the reproductive rate. The short-term decline of annual catches is slightly less than 10% for a small change in the rate of reproduction and reaches almost 20% for both fleet types when the reproductive rate is reduced by a larger margin. A comparison with a later simulation time period reveals that the short-term reduction in average annual catches is only the beginning of 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 as large as coastal vessel catches. 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 development of capelin catches also shows an overall trend that is negative (Tab. 2). However, the long-term impact is less extensive than for the cod catches, owing to the quicker adjustment of capelin to the new population dynamics, to reduced cod stock size, and the subsequent release of predation pressure.

time period change of the rate of reproduction	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
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

Table 3. Development of the net present value of profits when the rate of reproduction is reduced.

The net present value of discounted profits in the period of years 50 to 64 changes only very little despite considerable adjustments in stock sizes and landings caused by the changes in population dynamics (Tab. 3). Since the large differences in economic returns from fishing only start to occur 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 of the reproductive rates are more pronounced (Tab. 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 of the rate of reproduction. In contrast, the capelin fishery is affected to a lesser degree. 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 the opposite for cod due to discounting. The particularly bad years of the cod fishery are emphasized, while they receive less attention in the capelin fishery since they occur near the end of the period of interest. However, the overall negative development of all fisheries caused by reductions of reproductive rates remains evident in all scenarios despite the influence of discounting.

Decrease of the environmental carrying capacities

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

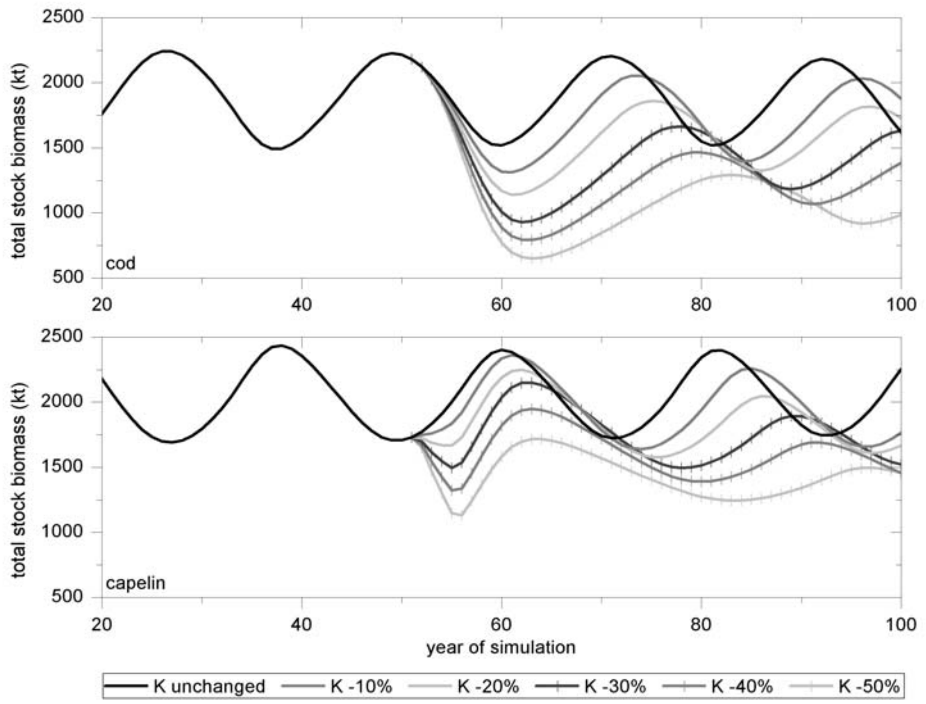

Figure 3. Development of the stock sizes with reduced carrying capacities.

The impact of a reduced carrying capacity on the development of capelin is less extensive. With the stock biomass already fluctuating substantially in the reference scenario, only a reduction of the carrying capacity by 30% or more causes the stock size to clearly deviate downward from the original range of fluctuation (Fig. 3). The reduction of the carrying capacity causes an initial decline of the stock compared to the increase in reference scenario. After that, there is a subsequent rise in biomass which can be attributed mainly to the concurrent strong decline of the cod stock. This causes much smaller losses of capelin due to 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.

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

time period	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
change of the carrying capacity	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
years 30-44	168.7		74.1		1022.3	
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%

Table 4. Development of annual catches when the environmental carrying capacity is reduced.

time period	**trawlers** (cod)	**coastal vessels** (cod)	**purse seiners** (capelin)
change of the carrying capacity	net present value of profits (million Nkr)	net present value of profits (million Nkr)	net present value of profits (million Nkr)
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

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

In contrast, catches of capelin are less affected by a change in the carrying capacity than by a reduction of the rate of reproduction. For slight declines of the carrying capacity, average capelin landings during the first decade remain practically unchanged (Tab. 4). Compared to the reference scenario, the average harvest amounts remain fairly stable in the long run, with average harvest amounts still totaling more than 70% of the original value even for a large reduction of the 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 (Tab. 5). This is primarily due to the increased cod fleet fishing effort, 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 behavior leads to significantly reduced predation on capelin. More capelin remains available for harvesting, which increases annual profits of the capelin fishery.

The long-term impacts of the change in the environmental carrying capacity are bleak for the cod fishery (Tab. 5). Whereas coastal vessels remains profitable if the carrying capacity of cod is reduced only a little, the cod fishery is not profitable for trawlers after a substantial decline of the carrying capacity. In the long run, the capelin fishery can even profit from the change in population dynamics: the net present value of profits is higher than in the reference scenario if the cod reduction has occurred to allow impaired 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 the rates of reproduction and the environmental carrying capacities to be affected at the same time so that both 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 of the rates of reproduction has only a small additional effect on the net present value of profits. Considering the time period immediately following the change in population dynamics, discounted profits are very similar for a given change in the carrying capacity regardless of the extent of the change in the reproductive rates. The increase of the trawlers' increase in fishing effort to stabilize profits despite a decreasing cod carrying capacity can be observed in all scenarios, regardless of the magnitude of an additional change in the cod rate of reproduction. In the long run, however, a combination of reductions in reproductive rates and carrying capacities of the two species causes the cod fisheries of both fleets to become unprofitable while profits of the purse seine fishery remain positive for the remainder of the simulations.

Influence of the share of capelin devoted to human consumption

Traditionally, most Norwegian capelin catches are used in the production of fish meal and oil. In recent years, there has been an increase in the amount of capelin that is exported and used for human consumption. Close to 50 per cent of the capelin landed by Norwegian fishermen was exported in 1999 (Statistisk Sentralbyrå, 2002) with the market price being up to seven times as high as the price for capelin that is 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%. Consequently, the market price of capelin increased with more capelin being used for exports. We assume that capelin market price used industrially $P_{cap,ind}$ is Nkr (Norwegian Crowns) 0.60 per kg while the capelin market price used for consumption $P_{cap,hum}$ is Nkr 4.20 per kg, so the average price level of capelin in the simulations turns out to be between 0.60 and 2.40 Nkr per kg.

average market price of capelin (Nkr / kg)	*years 30-44* net present value of profits (million Nkr)	*years 50-64* net present value of profits (million Nkr)	*years 70-84* net present value of profits (million Nkr)
0.60	695.1	616.7	613.4
0.96	1180.5	1055.2	1049.9
1.32	1666.0	1493.7	1486.4
1.68	2151.4	1932.1	1922.9
2.04	2636.9	2370.6	2359.4
2.40	3122.3	2809.1	2795.9

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

Simulations with different capelin price levels show that the amount of capelin caught in each fishing period does not change despite increased value of the resource. This is because in all scenarios the purse seine fleet utilization is high so there is little room to expand fishing effort. However, the net present values of profits of the capelin fishery increase substantially (Tab. 6) for a higher average price of capelin during all time periods of the simulations. If only 10 per cent of capelin is on average used for human consumption, the net present values of profits are already almost doubled. On the other hand, the cod fishery remains virtually unaffected by changes in the price level of capelin as landings and profits from fishing practically do not change.

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, no change in population dynamics occurs to ensure comparability between the scenarios. Net present values of profits are calculated for the three time periods of interest. Results indicate that the relation 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 is exemplary 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 the fleet type. Low discount rates lead to the worst overall net present value which is negative due to the losses of the trawlers and coastal vessels (Tab. 7). High discount rates only favor the net present value of profits of capelin fishing fleets while the economic results of cod fishing fleets are diminishing. 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 fishing fleets. The scheme is different for the capelin purse seine fleet. The size of the capelin stock and therefore landings show much higher fluctuations than the cod stock and cod catches. Consequently, the profitability of the capelin fishery tends to increase with higher discount rates, since good fishing years at the beginning of the period of interest are offset to a lesser degree by worse harvest yields following only a few fishing periods later.

discount rate	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
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	1053.0
13 %	458.9	247.2	1246.3
15 %	-98.4	46.0	1397.8

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

Influence of the learning factor

We examined the importance of the speed at which the fishermen adjust their harvest strategies is assessed. Even without changes in the population dynamics, the economic result of a fishing fleet changes depending on the speed at which fishermen utilize new information about the development of fish stocks.

learning factor	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
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

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

A learning factor of 0.5 used in the simulations, leads to a solid overall economic result with similar net present values of profits the same 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 this speed of strategy adjustment. For the purse seine vessels, it is advantageous to utilize information on the population dynamics of the capelin stock as fast as possible (Tab. 8) even though there are only little differences between the returns from fishing regardless of the learning factor.

Relying only on the long-term development of the cod stock leads to very bad economic results that might even include overall losses (Tab. 8). For the cod fishers, it is best to utilize a fair extent of newly gained information, i.e. to place a higher weight on the actual stock development than on the previously applied expected stock growth rates when updating the expected reproductive rate. The best economic result of trawlers is achieved with learning factors of 0.8 or 0.9 respectively. However, for coastal vessels, which target slightly older age classes than trawlers, the importance of previous experience of the fishermen is greater. Their best economic results are obtained for lower values of λ between 0.3 and 0.4.

5 Discussion and conclusion

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

Capelin decline less than cod. The extent of the decline is about the same for both kinds of changes 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 of the predation pressure. To a large part, this offsets the initial effect of the 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 long-term impacts of changes in population dynamics. Discounting causes years with high catches at the beginning of the 15-year period to be more important compared to years with lower catch sizes at the end of this 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. The increase of fleet utilization results in a short-term economic gain so that returns remain at the same level as in the reference scenario. The strategy of increasing fleet utilization to preserve large landings is rather short-sighted. Catch sizes and profits can be kept stable at a high level only for a few years longer despite a 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 are clearly evident. The net present value of profits during years 70 through 84 shows that the more valuable cod fishery is much more affected by negative developments in the stock size 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 harvest amounts can no longer be sustained.

A comparison of the simulations' 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 tons and cod landings total roughly 450 000 tons, most of which is caught by trawlers (cf. ICES, 2003a; Michalsen, 2004). In the simulations, the cod stock biomass averages about 1.9 million tons in the reference scenario and annual harvests amount to somewhere around 250 000 tons. In contrast, there are larger discrepancies between model results and observed values for the capelin stock and the amount of capelin harvested. The model generally overestimates the capelin stock size which causes the capelin purse seine catch and the subsequent economic result of this fishery to be too high. A possible reason for this discrepancy between the 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 the 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 can be found in the Barents Sea only rather infrequently, their predation leads to a smaller adult capelin stock and increased variability in the capelin biomass in subsequent years.

Another difficult aspect of the model setup is to represent the harvest strategies of the fishermen in a fairly realistic way. In this model version, the harvest strategies are not based on rational behavior that only considers the 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. Since 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 the fishing efforts are determined. Logistic stock growth functions were used in the calculation of the 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 on the stock development. As the determination of harvesting strategies and the calculations involving the population dynamics of the two species are conducted independently, no problems arise from the use of two different underlying biological models in the two contexts. This setup actually allows the assessment of different harvesting strategies of varying complexity without changing the update rules used to describe the stock development.

In the long run, adaptive harvesting strategies seem more sustainable than profit-maximizing harvesting 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 the development of the stock size. This holds particularly in cases in which restrictions to the adaptation rule cause the adjustment of fishing effort to be too slow to ensure a 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 reduction in the rates of reproduction or the environmental carrying capacities on the cod and capelin stocks in the Barents Sea and the catches of their fisheries. Further development of the model will be conducted in order to be able to get 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 analyze particular scenarios that arise from changes in climatic or hydrographic conditions.

Acknowledgements

This study is part of the research project INTEGRATION to assess the impacts of a possible shutdown of the thermohaline circulation which is funded by the German Ministry of Education and Research (project no. 01 LD 0016). The authors would like to thank two referees for valuable input and comments.

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Appendix A. List of symbols used in the model.

symbol	meaning
a	index denoting the age class
A	highest age class of a species
B	Biomass
cap	index referring to capelin
cod	index referring to cod
D	prey density
e	fleet utilization
g	rate of reproduction
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 the 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 the species
SSB	spawning stock biomass
sw	spawning weight
t	index denoting the fishing period
v	number of vessels
w	Weight
α	parameter used in recruitment function
β	parameter used in recruitment function
δ	discount factor
θ	variable costs
Θ	cost per unit effort
$\kappa 1$	rate of predation
$\kappa 2$	parameter used in calculation of predated biomass
λ	learning factor
μ	share of mature individuals
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 B. Parameters and initial values used in the simulations.

parameter	**value**	**source**
population dynamics of capelin		
initial number of individuals in each age group $n_{cap,a,0}$	[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 $w_{cap,a}$	[0.0036 0.0102 0.0182 0.024 0.0265] kg	based on ICES (2003b)
proportion of mature individuals $\mu_{cap,a}$	[0.00 0.01 0.41 0.87 1.00]	based on ICES (1999)
mean spawning weight per age class $sw_{cap,a}$	[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 rate of reproduction $g_{cap,0}$	0.5	
initial value carrying capacity $K_{cap,0}$	10 million t	
initial value recruitment parameter $\alpha_{cap,0}$	4491	set to be consistent with initial carrying capacity
initial value recruitment parameter $\beta_{cap,0}$	9	set to be consistent with initial carrying capacity
population dynamics of cod		
initial number of individuals in each age group $n_{cod,a,0}$	[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 $w_{cod,a,0}$	[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 mature individuals $\mu_{cod,a}$	[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 $sw_{cod,a,0}$	[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 data
natural rate of survival χ_{cod}	0.8	Sumaila (1995)
initial value rate of reproduction $g_{cod,0}$	0.5	Eide (1997)

parameter	value	source
initial value carrying capacity $K_{cod,0}$	6 million t	Sumaila (1995)
initial value recruitment parameter $\alpha_{cod,0}$	682	set to be consistent with initial carrying capacity
initial value recruitment parameter $\beta_{cod,0}$	1.5	set to be consistent with initial carrying capacity
parameters relating to the predator-prey-relationship		
maximum value of $D_{cap,t}$: $D_{cap,max}$	1.5	Moxnes (1992)
standard biomass of capelin $B_{cap,std}$	4.467 million t	Moxnes (1992)
rate of weight increase of cod $\hat{w}_{cod,a}$	[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}	15.12 million Nkr	Sumaila (1995)
variable costs θ_{TR}	12.88 million Nkr	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}	0.65 million Nkr	Sumaila (1995)
variable costs θ_{CV}	0.88 million Nkr	Sumaila (1995)
economic parameters of purse seine vessels		
fleet size v_{RW}	70	adapted from Statistisk Sentralbyrå (2002)
catchability coefficient q_{RW}	0.0175	adapted from Sumaila (1997)
fixed costs φ_{RW}	0.42 million Nkr	adapted from Sumaila (1997)
variable costs θ_{RW}	0.58 million Nkr	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 / kg	based on Fiskeri-direktoratet (2001)
market price of capelin that is used for consumption $P_{cap,hum}$	Nkr 4.20 / kg	based on Fiskeri-direktoratet (2001)
market price of cod P_{cod}	Nkr 6.78 / kg	Sumaila (1995)
learning factor λ_s	0.5 for all fleets	

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