Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies

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Abstract

Consequences of changes in fish population dynamics of commercially exploited species are not limited to biological impacts such as a diminishing standing biomass or a reduced reproductive success but extend to possible economic losses incurred by the harvesting fleets. Using a bioeconomic model of the cod and capelin fisheries of the Barents Sea, this study assesses the role of the fishermen's behavior in offsetting or pronouncing the effects on the stocks caused by altered population dynamics. Adaptive harvesting strategies, in which the fishing effort depends on the harvesting success of the previous fishing period, and rational behavior, i.e. the maximization of profits in the current fishing period, are considered. All scenarios cover a time period of 100 years with sudden changes of the rates of reproduction of both species occurring at the midpoint of each simulation. Stock sizes and landings of fish are determined for each fishing period, and the net present value of profits over a 15-year time period following the change in population dynamics is calculated. Results show that with adaptive harvesting strategies, a negative development of the stocks adversely affects all fleets with the cod fishery generally being impacted to a greater extent than the capelin fishery. If harvest strategies are driven by profit maximization, a negative development of the cod stock can turn out to be beneficial to the capelin stock and its fishery. Also, changes in the age composition of the cod stock brought about by fishing activities in combination with a less successful biological development of the stock can render the cod fishery unprofitable leading to the shutdown of the fishery.

Key words

bioeconomic modeling, Barents Sea, cod, capelin, population dynamics, harvesting strategy

Introduction

Changes in the population dynamics of fish can be brought about by altered environmental conditions. Shifts in temperature, salinity, or oxygen content have a direct influence on the reproductive success of fish species. Lower rates of reproduction lead to diminishing standing stock sizes and can sometimes even cause complete stock collapses, especially if the stocks are subject to commercial exploitation by humans. However, this is by no means a mandatory consequence: the choice of the harvesting strategy by the fleets involved in the exploitation of the stocks has a profound impact on the development of the exploited species.

The Barents Sea fisheries of cod (*Gadus morhua*) and capelin (*Mallotus villosus*) have been subject to several studies in the recent past. This is mainly due to the particular importance of the cod fishery for the Norwegian economy and the well-documented history of both stocks which allows for a more reliable model validation. Sumaila (1995) developed a bioeconomic model of the cod fishery which was later expanded to capture he predator-prey relationship between cod and capelin (Sumaila, 1997). This model is used to determine the economically optimal harvesting strategies for various economic boundary conditions. Results show that a joint harvesting strategy that encompasses both species leads to higher profits from fishing than non-cooperative exploitation. Eide (1997) and Armstrong & Sumaila (2000) highlight the importance of biological feedbacks such as predation and cannibalism within the cod stock. Simulations lead to the conclusion that an economically optimal exploitation of the cod stock can only take place if the effect of cannibalism on the stock development is not neglected (Eide, 1997).

Models that focus on the development of the capelin stock are e.g. CAPELIN (Tjelmeland, 1985) and BIFROST (Gjøsæeter *et al*., 2002). These are single-species models used to assess the short-term development of the capelin stock under commercial exploitation. The bioeconomic multi-species model ECONMULT was presented by Eide & Flaaten (1993). An aggregated version of the model (Eide & Flaaten, 1994) was used to show that the economically optimal exploitation of the cod and capelin stocks consists of harvesting both species instead of focusing on the more valuable cod and leaving the less valuable capelin in the sea as food source for its predator.

All studies mentioned above look at the economic results of fishing activities for various economic boundary conditions. The environmental conditions, on the other hand, are held constant. Since the simulation periods of the bioeconomic models is usually limited to a few years or decades, changes in environmental conditions do not have to be considered explicitly (Knowler, 2002). However, changes in the development of the commercial fish stocks due to natural variability or long-term shifts in hydrographic conditions can have severe economic consequences for the fisheries engaged in their exploitation. Moxnes (1992) analyzes the development of the Barents Sea cod and capelin fisheries under uncertainty. He shows that the uncertainty stemming from random variation, measurement errors or parameter uncertainties can lead to qualitatively different simulation results for the same initial conditions, calling for fundamentally different management strategies necessary for optimal stock exploitation. Mackinson *et al*. (1997) emphasize the importance of the harvesting strategy for optimal stock management, especially if the stock size of the exploited species is reduced to very low levels. In an analysis of the behavior of fishermen harvesting small schooling pelagic fish species in periods of stock collapse they show hat in density-dependent catchability models a profit maximizing harvesting strategy can lead to an increased incidence of complete stock depletion since the fishermen maintain high levels of fishing efforts even if the stock size is in decline.

Changes in the population dynamics of fish caused by shifts in environmental conditions can severely impact the development of commercially exploited species. The harvesting strategies of the fishermen can impose an additional pressure on the stocks. Depending on the strategy chosen, anthropogenic harvesting activities can magnify the natural effect or contribute to an alleviation of the consequences of the change in population dynamics. This study examines the role of the harvesting strategy in the development of the Barents Sea cod and capelin stocks in situations of reduced reproductive success. Two general patterns of fishermen's behavior are considered: using adaptive harvesting strategies, the fishermen determine the extent of the fishing effort based on the economic result of the previous fishing periods. Rational behavior, i.e. harvesting strategies that are based entirely on profit maximization, disregards any past experience. Effort levels are determined solely on the basis of reaching the maximum possible economic returns from fishing in the current fishing period. In the following section, the fisheries of cod and capelin in the Barents Sea are briefly described. The model used in this assessment is presented in the subsequent section. The results of the model simulations examine the consequences of changes in the rate of reproduction in both species. In the discussion of the results, the particular impact of each harvesting strategy on the development of the stocks and the fisheries in situations of inhibited population dynamics is assessed.

The cod and capelin fisheries in the Barents Sea

The Arcto-Norwegian cod stock is one of the most important commercially exploited fish stocks in the world (Sumaila, 1995) and undoubtedly the most valuable stock in the Barents Sea. It is jointly managed by fleets from Norway and Russia. In recent decades the stock biomass has shown considerable variability. Long-term increases in fishing activity have led to a decline in stock size from more than 3 million tons in the 1950s to about 1 million tons in the 1980s (ICES, 2003a). Short-term increases since then can be attributed to particularly successful recruitment of new age classes (Mehl & Sunnanå, 1991). Cod is caught by large trawlers and numerous smaller coastal vessels. At present, annual catches of cod total slightly more than 400 000 tons (ICES, 2003a). About 270 000 tons are caught by the 60 trawlers, the remaining 150 000 tons are landed by the approximately 640 coastal vessels currently in operation.

The capelin stock shows even larger fluctuations owing to its short life-span and the considerable predation pressure by cod. The stock size was relatively stable in the 1970s at roughly 4 million tons before being reduced to less than 200 000 tons in the 1980s and mid-1990s (Gjøsæter *et al*., 1998). Significant increases in stock biomass, as observed in the early 1990s are caused by the recruitment success of only one or two age classes and did not have a lasting impact. Annual catches rose steadily from the 1960s until the mid-1980s always exceeding 1 million tons, but dropped sharply over the course of only a few years, so that the capelin fishery needed to be closed from 1987 to 1990 (ICES, 2003b). Capelin was caught again for a few years in the early 1990s but fishing activities were halted again from 1994 through 1998. At present, harvesting of Barents Sea capelin has resumed but annual landings remain at comparably low levels.

The model

In general, bioeconomic models of fisheries assess the magnitude of returns from fishing in a variety of scenarios with different economic boundary conditions. Environmental conditions are usually considered to be constant, a reasonable assumption if the simulation period covers only a few years or a couple of decades. The model used in this study covers a longer time period. Changes in environmental conditions are assumed to influence the development of the stocks by affecting the rates of reproduction or the environmental carrying capacities of the species.

Two species are covered in the model: cod and capelin. The cod stock is exploited by two competing vessel types, trawlers and coastal vessels. Since the purse seine fishery is the dominating form of capelin fishery, only this vessel type is considered here. The simulations of the model extend over a time horizon of one century. It is assumed that at the midpoint of each simulation, a sudden change of the reproductive rate of both species occurs which remains in effect until the end of the simulation period. For reasons of comparability of the scenarios, inter-annual natural variability of recruitment success and survival rates of the individual age classes are disregarded. For each fishing period the variables concerning the development of the stock size and the economic exploitation of the two species are determined. The scenarios are compared to a reference case in which the population dynamics remain unaltered. A detailed description of the model including the main equations and parameterizations is given by Link & Tol (2003).

Population dynamics of cod and capelin

The model follows the general setup of Moxnes (1992) and Sumaila (1997) by distinguishing 15 age-classes for cod and 5 for capelin. Recruitment into the lowest age class depends on the stock size at the end of the harvesting period after all factors leading to a decrease in stock size (harvesting, cannibalism, and predation) have been taken into account.

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

The number of recruits is determined by using a Beverton-Holt recruitment model (Beverton & Holt, 1954) where the parameters *α* and *β* are set such that in the reference scenario the equilibrium biomasses without fishing activities would be 6 million tons for cod (Sumaila, 1997) and 10 million tons for capelin.

Individuals that survive the fishing period and do not die from natural causes comprise the next higher age class in the subsequent fishing period. All individuals of the cod stock reaching or exceeding the age of 15 accumulate in the highest age class since it is assumed that cod does not grow anymore after reaching this age.

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

The weight increase of cod is variable and depends on the amount of capelin consumed, a relationship already documented by Magnússon & Palsson (1991). In the model, the extent of predation is mainly dependent on the density of prey *D* and the number of predators.

The fisheries

For each fishing period and vessel type, the number of individuals removed from the stock by harvesting is calculated. The harvest amount is a function of the fleet size *v*, the fishing effort *e* and the stock size given by the number of individuals in each age class *n*. Since each fleet is assumed to catch only particular age classes, the harvesting activities of the fleets, described by the catchability coefficients *q*, all have characteristic impacts on the stocks.

(3) $$h_{s,i,a,t} = q_{s,i,a} n_{s,a,t}^{init} v_{s,i} e_{s,i,t}$$

Based on the number of fish caught, the weight of the entire catch *w* in each fishing period can be deduced. It is assumed that the demand curve is perfectly elastic, i.e. the market prices of fish *P* remain constant regardless of the quantities landed. The total costs of fishing are made up of fixed costs *φ* for the maintenance of the fleet which are independent of the fleet utilization and variable costs that are directly related to the extent of fleet utilization *θ*.

(4) $$\pi_{i,t} = \sum_{s,a} P_{s,i} h_{s,i,a,t} w_{s,a,t} - v_i \left(\varphi_i + e_{i,t}\theta\right)$$

Profits of each fleet are obtained by relating revenues from fishing to total costs of operation. In this study, the profits from fishing during three different time periods of 15 years each are of special interest: the period of years 30 through 44, the period immediately after the change in population dynamics (years 50 through 64), and the period between years 70 and 84. A time-independent discount factor δ is used for weighting purposes. The length of the period of interest was selected to be 15 years since this duration roughly corresponds to the time period over which a vessel is utilized.

(5) $$\Pi_i = \sum_{t=t_0}^{t_0+15} e^{-\delta(t-t_0)} \pi_{i,t}$$

The control variable is the fishing effort that is exerted during each fishing period. The boundary conditions for the economic exploitation of the fish stocks are given by the population dynamics of the two species that are described earlier.

The harvesting strategies of the fishermen

Two different harvesting strategies of the fishermen are distinguished. The adaptive strategy is based on the principle that the fishing effort of each fishing fleet is adjusted after each fishing period according to the economic success in the previous fishing period. The success is measured by comparing the actual catch of each fleet to a previously calculated target catch size. This target catch size is based on the maximum sustainable yield of the species. If the amount of fish landed is less than the target catch size, the fleet utilization s increased in the following fishing period. It is taken as a rule that this increase is 10 per cent of the utilization of the previous fishing period. If the amount caught exceeds the target catch size, the fleet utilization during the following year is reduced by the same amount.

In contrast, fishermen can follow a strategy of profit maximization in the current fishing period (rational behavior). In this case the fleet utilizations of all vessel types are determined based on the given stock sizes and economic boundary conditions such that the total profits from fishing activities of all three fleet types together are maximized. There is no relationship between the fleet utilization of two subsequent years. It is also assumed that there is perfect information, i.e. the stock sizes and age distributions of both species at the beginning of the harvesting period are known.

Results

A series of simulations is conducted for various degrees of reduction of the rates of reproduction for both harvesting strategies. The average number of individuals in each age class during the time period from 1993-2003 for cod (ICES 2003a) and 1992-2002 for capelin (ICES 2003b) was used as initial age distribution of the stocks. At year 50 of each 100-year simulation the rate of reproduction was reduced for both species by a certain amount and held at the new level for the rest of the simulation period.

Adaptive harvesting strategies

A decline of the rates of reproduction of both species leads to smaller stock sizes of both cod and capelin. The cod stock decreases by roughly one third if the rate of reproduction was to shrink by 50% (Fig. 1). 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 with a smaller total stock biomass.

The development of the capelin stock follows the same general pattern (Fig. 2). In the reference scenario, the overall stock biomass fluctuates around an average value of approximately 1.5 million tons. For a reduction of the rate of reproduction by 50%, the average stock size decreases to roughly 1 million tons. The impact of the change of the rate of reproduction on the capelin 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.

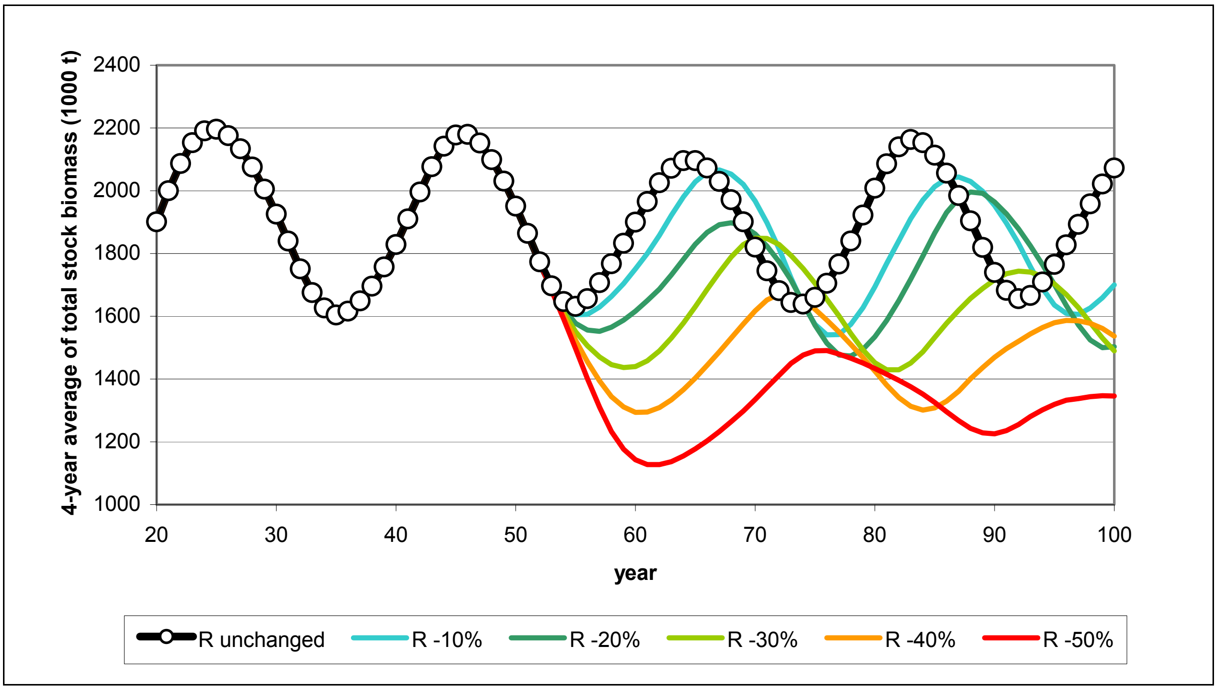

Fig. 1: development of the cod stock size when an adaptive harvesting strategy is employed

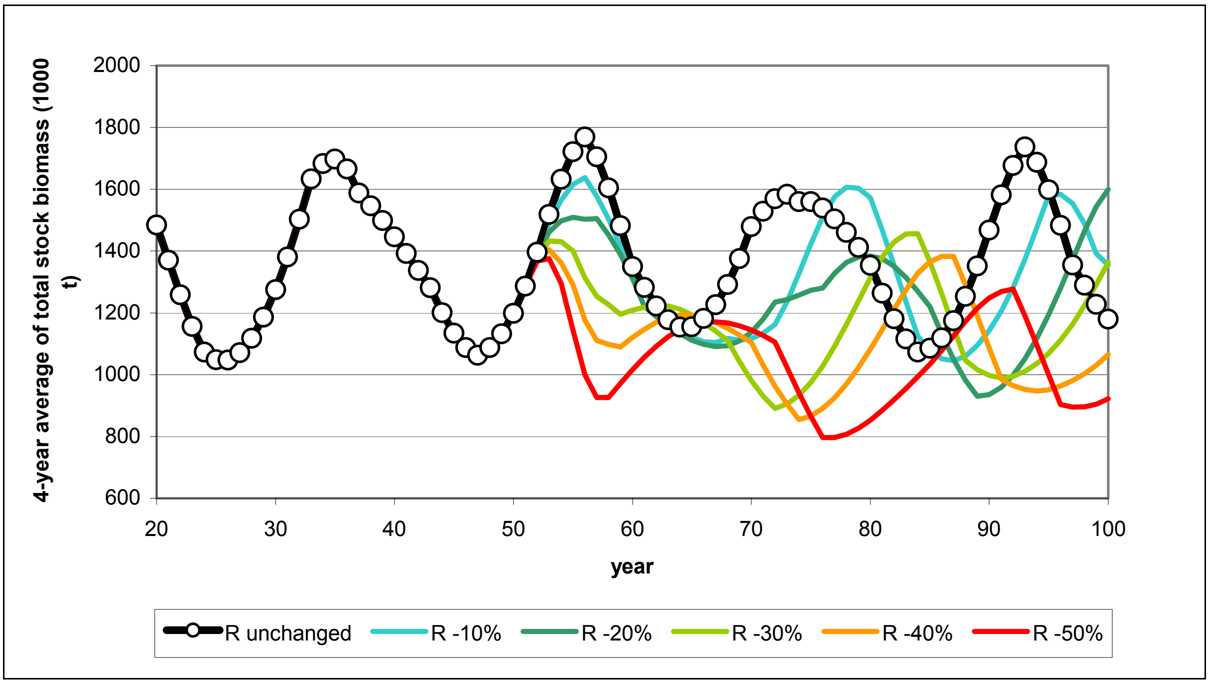

Fig. 2: development of the capelin stock size when an adaptive harvesting strategy is employed

Consequently, annual catch sizes of both the cod and capelin fisheries decline in size. Compared to the reference scenario, in which the catches of cod fluctuate around 150 000 tons of fish caught by trawlers and a little less than 100 000 tons per year caught by coastal vessels (Tab. 1), catches decline notably even for small reductions of the rate of reproduction. For a large reduction of the reproductive rate, the short-term decline of annual catches is about 20% for both fleet types. A comparison with a later time period of the simulation reveals that the short-term reduction in average annual catches is only the beginning of a negative trend that in the long-run leads to a decline in catches by up to three quarters. It has to be noted that initially, cod catches by trawlers amount to more than twice as much fish as landings by coastal vessels. By the end of the simulation period this ratio changes in favor of the coastal vessels in all scenarios. The extent to which the gap between the amounts caught by the two vessel types closes is particularly pronounced in the scenarios with large changes in population dynamics.

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
year 30-44	155.5		67.5		476.1	
year 50-64						
reference scenario	148.0		80.7		455.2	
R -10%	136.5	-7.8%	72.8	-9.8%	441.9	-2.9%
R -20%	131.0	-11.5%	69.7	-13.6%	423.6	-6.9%
R -30%	125.8	-15.0%	67.0	-17.0%	417.5	-8.3%
R -40%	121.1	-18.2%	65.1	-19.3%	400.7	-12.0%
R -50%	116.0	-21.6%	63.0	-21.9%	388.0	-14.8%
year 70-84						
reference scenario	122.4		98.9		479.3	
R -10%	115.4	-5.7%	85.9	-13.1%	443.7	-7.4%
R -20%	102.0	-16.7%	69.6	-29.6%	388.4	-19.0%
R -30%	84.4	-31.0%	65.8	-33.5%	292.4	-39.0%
R -40%	65.4	-46.5%	49.1	-50.4%	297.0	-34.8%
R -50%	33.3	-72.8%	25.5	-74.2%	264.8	-44.8%

Tab. 1: development of annual catches when an adaptive harvesting strategy is employed

The development of the capelin catches also shows an overall trend that is negative (Tab. 1). However, the impact is much smaller than for the cod catches. Even for a reduction of the reproductive rate of 50%, the short-term change of capelin catches is only 15%, while the maximum reduction of capelin catches in the simulations in the long-run was around 40%. That the overall impact on the capelin stock and on capelin landings is less than on the capelin stock, can be attributed to the quicker adjustment of capelin to the new population dynamics and in most scenarios to a reduced cod stock size and the subsequent release of predation pressure.

The net present value of discounted profits in the period of years 50 to 65 remains largely unaffected by changes in population dynamics despite considerable adjustments in stock sizes and landings (Tab. 2). This is due to the fact that in the calculation of the net present value of the profits the first years in the period of interest are weighted higher than the later years of this period. However, 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 if only the period immediately after the onset of the environmental change is considered.

The long-term economic consequences are more severe. All three vessel types suffer considerable reductions in profits (Tab. 2). In all scenarios with changed population dynamics the trawl fishery becomes largely unprofitable. The same holds true for the coastal vessels in case of a large reduction of the rate of reproduction. In contrast, the capelin fishery is seems to be 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 capelin catches are relatively high around year 70 and lower at year 84, whereas the situation is the opposite for cod. The effect of discounting in this case is that 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 changes in population dynamics remains obvious in all scenarios despite the influence of discounting.

time period	trawlers (cod)		coastal vessels (cod)		purse seiners (capelin)	
change of the rate of reproduction	NPV (million NOK)	change from reference scenario	NPV (million NOK)	change from reference scenario	NPV (million NOK)	change from reference scenario
year 30-44	613.4		340.1		251.4	
year 50-64						
reference scenario	443.1		457.9		298.7	
R -10%	442.6	-0.11%	457.7	-0.04%	298.4	-0.10%
R -20%	442.0	-0.25%	457.5	-0.09%	297.8	-0.30%
R -30%	441.4	-0.38%	457.3	-0.13%	298.2	0.17%
R -40%	440.8	-0.52%	457.1	-0.18%	297.8	-0.30%
R -50%	440.1	-0.68%	456.8	-0.24%	298.2	-0.17%
year 70-84						
reference scenario	291.0		575.5		326.7	
R -10%	-8.8	-103.0%	460.5	-20.0%	282.4	-13.6%
R -20%	-313.3	-207.7%	283.8	-50.7%	139.8	-57.2%
R -30%	-834.0	-386.6%	-45.7	-107.9%	213.4	-34.7%
R -40%	-1102.0	-478.7%	-241.5	-143.3%	167.3	-48.8%
R -50%	-1266.8	-535.3%	-394.4	-168.5%	104.0	-68.2%

Tab. 2: development of the net present value of profits when adaptive harvesting strategies are employed

Profit maximizing harvesting strategies

The consequences of changes in the reproductive rate are quite different if fishermen follow the strategy of maximizing the joint profits of the current fishing period. The fact that fleet utilizations of two subsequent years have no relationship to each other (in contrast to the adaptive harvesting strategies) causes higher fluctuations in landings and consequently less predictable changes in the stock sizes.

The relationship between the change in population dynamics and the stock size development is less clear with profit-maximizing harvest strategies than with adaptive strategies. For small changes in population dynamics, the size of the cod stock remains largely unaffected at an average level of roughly 1.5 million tons of biomass (Fig. 3), the only clear sign of the change in population dynamics is the increased variability in the stock development. For larger changes in population dynamics, the resulting trend is fairly clear: the stock size diminishes by one third to one half and then stabilizes at the new reduced level.

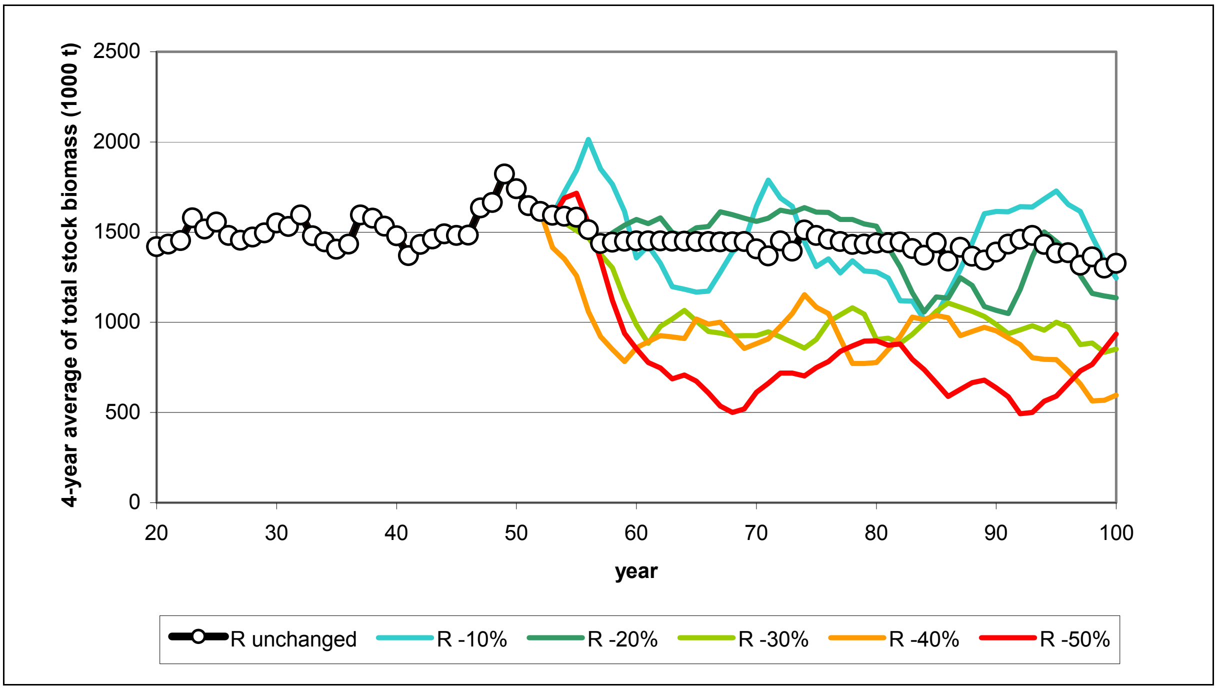

Fig. 3: development of the cod stock size when a profit-maximizing harvesting strategy is employed

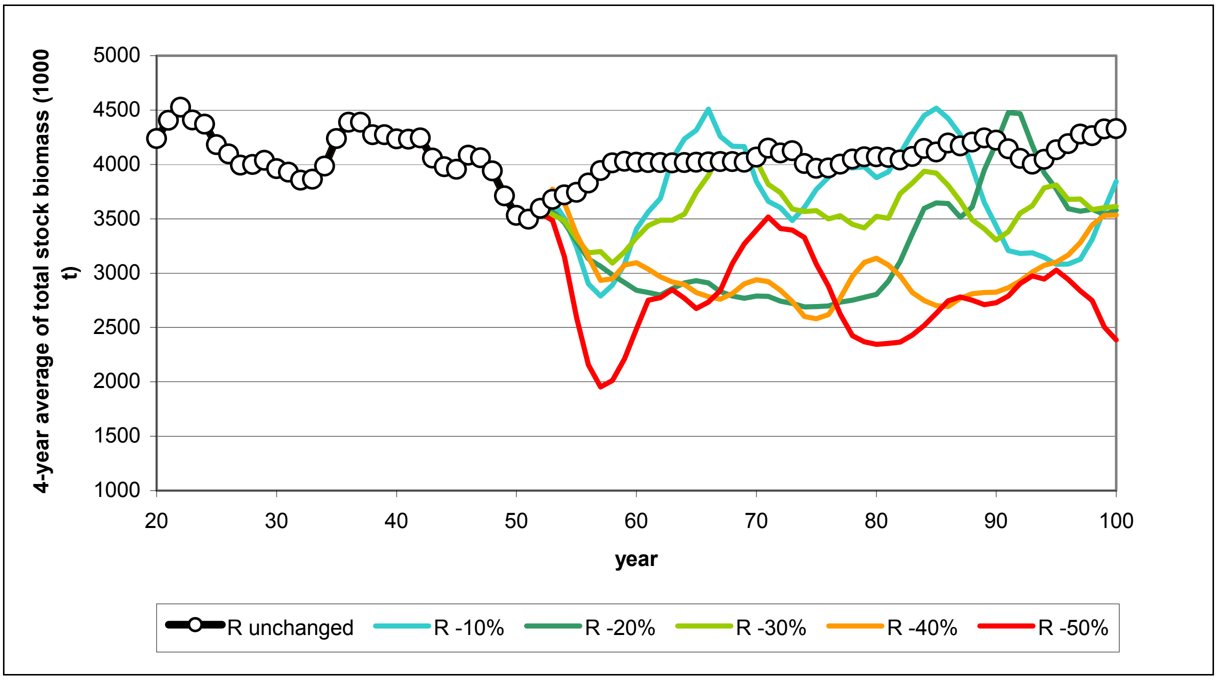

Fig. 4: development of the capelin stock size when a profit-maximizing harvesting strategy is employed

The capelin stock is adversely affected by changes in population dynamics in all scenarios with a strong decline taking place in the first few years after the onset of the change (Fig. 4). In some cases the capelin stock can recover. This is usually the case when the cod stock is at particularly low levels and the increase in capelin stock size is mainly attributable to less predation by cod. In the scenarios with a large reduction of the rate of reproduction the capelin stock size decreases by one third to one half. This is slightly more than in the scenarios with adaptive harvest strategies but it has to be considered that the equilibrium capelin stock size before the change in population dynamics is more than twice as large as in the other set of scenarios. The reason lies only in the different strategy of exploiting the stock since control runs without fishing activities lead to the same equilibrium stock sizes in both sets of simulations.

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
year 30-44	234.0		55.2		809.5	
year 50-64						
reference scenario	221.5		25.4		927.1	
R -10%	158.2	-28.6%	78.5	+209.1%	751.2	-19.0%
R -20%	106.7	-51.8%	82.5	+224.8%	707.8	-23.7%
R -30%	175.9	-20.6%	63.2	+148.8%	534.4	-42.4%
R -40%	134.0	-39.5%	46.3	+82.3%	809.4	-12.7%
R -50%	132.9	-40.0%	61.7	+142.9%	583.2	-37.1%
year 70-84						
reference scenario	219.9		16.0		1004.3	
R -10%	222.3	+1.1%	67.0	+318.8%	847.2	-15.6%
R -20%	167.8	-23.7%	33.3	+108.2%	683.8	-31.9%
R -30%	139.5	-36.6%	35.4	+121.3%	760.3	-24.3%
R -40%	99.5	-54.8%	37.7	+135.6%	777.3	-22.6%
R -50%	102.9	-53.2%	34.9	+118.1%	600.9	-40.2%

Tab. 3: development of annual catches when a profit-maximizing harvesting strategy is employed

Overall catches of cod decline with a reduction in the reproductive rate. This decline only affects the trawlers whose landings are cut in half in some scenarios (Tab. 3). On the other hand the coastal vessels' market share increases in all scenarios with changed population dynamics. However, this is only because of the extremely low average harvest amount in the reference scenario. In general, landings by trawlers are higher under profit-maximization whereas the importance of the coastal vessels is lower than with adaptive harvesting strategies.

The development of capelin catches follows directly from the development of the stock size. The increase in standing stock biomass at the beginning of the 100-year simulation period is due to the fact that it is considered to be optimal to refrain from harvesting capelin for some years to allow the buildup of the stock to levels of roughly 4 million tons of biomass (Fig. 4). This does not happen with adaptive strategies, so the equilibrium stock size is much lower in that set of simulations. The short-term impact of changes in population dynamics on capelin catches is much greater with profit-maximizing strategies (Tab. 3) but it has to be noted that the starting level with an average catch size of more than 900 000 tons per year is also much higher. The relative change in the long run, however, is quite similar with a reduction of average annual landings by approximately 40% when the rate of reproduction is cut in half.

In contrast to the change scenarios with adaptive harvesting strategies, the trends of the development of the net present value of discounted profits are less clear. Looking at the short-term impacts of changes in population dynamics, the profits of the trawl fishery of cod are negative even in the reference scenario (Tab. 4). In many cases the change in population dynamics magnifies the losses incurred. On the other hand, the coastal vessels profit from such changes to a certain extent. The capelin fishery is negatively affected by changes in the rate of reproduction of the fish species with a short-term decline in profits by 10 to 20% coinciding with the reduction in stock size and the resulting decrease in catches.

time period	trawlers (cod)		coastal vessels (cod)		purse seiners (capelin)	
change of the rate of reproduction	NPV (million NOK)	change from reference scenario	NPV (million NOK)	change from reference scenario	NPV (million NOK)	change from reference scenario
year 30-44	-22,9		130,3		307,6	
year 50-64						
reference scenario	-146,1		126,0		281,1	
R -10%	-350,3	-139,8%	147,0	+16,7%	253,0	-10,0%
R -20%	-163,3	-11,7%	120,5	-4,4%	286,8	+2,0%
R -30%	-159,8	-9,4%	139,3	+10,6%	242,7	-13,7%
R -40%	132,7	+190,8%	157,8	+25,2%	235,6	-16,2%
R -50%	-263,2	-80,2%	98,8	-21,6%	231,0	-17,8%
year 70-84						
reference scenario	-322,0		-207,6		371,8	
R -10%	62,0	+119,3%	488,7	+335,4%	37,2	-90,0%
R -20%	-261,2	+18,9%	-209,5	-0,9%	199,2	-46,4%
R -30%	-102,0	+68,3%	-168,1	+19,0%	405,6	+9,1%
R -40%	-555,0	-72,4%	-117,1	+43,6%	271,3	-27,0%
R -50%	-109,8	+65,9%	-173,2	+16,6%	35,1	-90,6%

Tab. 4: development of the net present value of profits when a profit-maximizing harvesting strategy is employed

The long-term economic consequences are extremely bad. The cod fishery is unprofitable in most scenarios. The exception is the scenario of a small reduction of the rate of reproduction (R -10%) that leads to a highly volatile stock development. By co-incidence, the period of interest covers a period that is characterized by a stock size and annual catches that are even higher than in the reference scenario. Therefore the economic result of the fishery in that scenario is particularly good. However, this scenario is not representative for the overall stock development. The capelin fishery also has to suffer reduced profits. But unlike the cod fishery the revenue from fishing always remains higher than the fishing costs. Similar to the cod fishery there is one scenario (R -30%) in which profits even increase. This is caused by the particularly stable development of the stock size and catches in the years prior to the beginning of the period of interest.

Discussion

The simulations show that regardless of the harvesting strategy, a reduction of the rates of reproduction of both species almost always negatively affects the standing stock biomasses. However, the economic consequences arising differ depending on the harvest strategy deployed. With adaptive harvesting strategies, the trawlers are affected by changes in population dynamics to a greater extent than the coastal vessels. Initially, the market share of the trawl fishery is much greater than that of the coastal vessels. When the change in population dynamics occurs, both vessel types have the same profitability and by the end of the simulations it is usually the case that coastal vessels obtain the greater returns from fishing than the trawlers. The situation is different with profit-maximizing harvesting strategies. In all scenarios the profitability of the coastal vessels surpasses that of the trawlers. The results suggest that because of the large operating costs of the trawlers, their operation becomes unprofitable if the biomass of the cod stock permanently falls below a certain threshold value of approximately 1.5 million tons.

The impacts on the capelin fishery caused by a change of the rate of reproduction are generally slightly higher under profit maximization when annual catches drop from a level of 900 000 tons to 500 000 – 600 000 tons whereas average annual landings for adaptive harvesting strategies decrease from an average of 500 000 tons to somewhere between 300 000 and 400 000 tons. It has to be noted that during the first two decades of the simulations under profit-maximizing harvest strategies it is preferable to focus more on the cod fishery than on capelin, a phenomenon not observed with adaptive harvesting strategies. This proves to be beneficial to the capelin stock and subsequently to the fishery since the stock can increase in size substantially which allows larger harvest amounts of capelin in later years.

The importance of the influence of the fisheries on the development of the cod and capelin stocks is emphasized by the fact that a control run in absence of fishing activities leads to stable stock sizes that are only marginally affected despite changes occurring in population dynamics. So generally, a reduction of the reproductive rate by itself would not have a particularly strong impact on the stock development since the sizes of both stocks are currently far from their natural equilibrium states. The fate of the stocks and subsequently of the fisheries exploring them is much more dependent on the strategies used in the harvesting activities. In most cases changes in population dynamics do not pose an immediate threat to the existence of the fisheries. It is, however, the responsibility of the fishermen to set their harvesting strategy such that a change in the population dynamics of the stocks does not make it necessary to abandon the fishing activities entirely for the lack of profitability.

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