

Working paper No. 52/10

**Climate Change and Credibility of
Fish Stock Agreements: The case of the
North-East Arctic Cod**

by

Nils-Arne Ekerhovd

SNF Project No. 5259
Expected Change in Fisheries in the Barents Sea

The Project is financed by the Research Council of Norway

INSTITUTE FOR RESEARCH IN ECONOMICS AND BUSINESS ADMINISTRATION
Bergen, December 2010
ISSN 1503-2140

© Dette eksemplar er fremstilt etter avtale
med KOPINOR, Stenergate 1, 0050 Oslo.
Ytterligere eksemplarfremstilling uten avtale
og i strid med åndsverkloven er straffbart
og kan medføre erstatningsansvar.

Climate Change and Credibility of Fish Stock Agreements: The case of the North-East Arctic Cod

Nils-Arne Ekerhovd

Samfunns- og Næringslivsforskning AS

[SNF, Institute for Research in Economics and Business Administration]

Breiviksveien 40, N-5045 Bergen, Norway, nilsarne.ekerhovd@snf.no

December 2010

Abstract

We simulate how an increase in the productivity of the North-East Arctic cod stock would affect the Russian-Norwegian cooperation on the management of the stock. The productivity increase is linked to environmental conditions in the sea and to climate change through a temperature-dependent stock-recruitment relationship, where the numbers of recruits is positively related to the sea temperature given the spawning stock biomass. Increased recruitment and productivity of the stock improved the stability of an agreement on joint management. Expressing the closed-loop solution as a series of open-loop equilibrium solutions, studying the issue of reevaluating agreements on shared and straddling fish stocks, highlights the need for better and more flexible management systems that can cope with shifting environmental conditions.

Keywords: Closed-loop game modeling; Noncooperative and cooperative solutions; North-East Arctic cod; Climate change

JEL Classification: C61; C73; Q22.

Introduction

How would the formation, stability and success of an agreement on cooperative management between neighboring coastal states for a climate-sensitive fishery resource be affected by changes in the abundance, distribution and accessibility of the resource within the exclusive economic zones (EEZs) of these states? A shift in the climate regime could have two types of effects on a climate-sensitive fishery resource: (i) changed biomass and (ii) changed area of distribution or/and migration pattern. Both are, of course, possible and closely linked. If the stock decreases in numbers, this may have an effect on distribution. Abundance changes may also have a density-dependent effect on catchability.

The inherent difficulty of managing such resources suggests that adaptation to the effects of climate variability and climate change is likely to be less complete and effective than might be the case for resources that are controlled by a soleowner. Moreover, climatic variations may destabilize efforts to cooperatively manage resources that are shared among several jurisdictions.

With regard to climate change and its effects on fisheries, the research has mainly been focused on changes in distribution of fish stocks that straddle the boundaries between different jurisdiction (Ekerhovd 2010; Miller 2007; Hannesson 2007b,c; Miller and Munro 2004). However, Brandt and Kronbak (2010) evaluated the possibilities of achieving a cooperative agreement for a jointly exploited resource if the resource itself is subject to an exogenous change. In an application to Baltic cod they show that if climate change increases the biomass of the stock, then there is an increased possibility of achieving a cooperative agreement (Brandt and Kronbak 2010).

Here we examine the temporal conditions for sharing of the North-East Arctic (NEA) cod fishery between Norway and Russia in the Barents Sea when warmer ocean temperature positively affects the productivity of the stock through increased recruitment to the fishery. The main focus is on the determination and comparison of two types of

solutions: noncooperative and cooperative solutions. We will compare the cooperative (Sole-Owner) alternative outcome with noncooperation over time as the temperature is assumed to increase and the numbers of recruits entering the fishery increases with it, given the spawning stock biomass.

In reality, Russia and Norway share the total allowable catch (TAC) of the NEA cod equally between them. (In addition, the treaty between Norway and Russia also includes haddock and capelin and allows for some minor share to be fished by third country vessels, which we will ignore in this context). Moreover, we will assume that Norway and Russia would both prefer to cooperate rather than compete for the fish if the net present value (NPV) from the cooperative solution would cover their opportunity costs of cooperating; that is, if the NPV from cooperation is sufficiently large to pay both countries the NPVs they would have earned on their own competing against each other. If not, we will assume that they will go on with the noncooperative behavior until cooperation becomes sufficiently profitable. Furthermore, the paper looks at a status quo case where there is no temperature/productivity change, in order to identify whether the decision to cooperate or not is really affected by changes in the stock productivity.

The change in productivity as the climate changes and the temperature increases is not necessarily a straightforward process. This, again, might shift the balance of the bargaining power between the coastal states. It might take years before the new status is generally accepted by the all coastal states, as the shift in temperature and recruitment can be a gradual process with considerable short term variation, meaning that there may be considerable doubt as to whether a shift in the productivity is only a temporary change or if the fish stock actually has changed its recruitment and productivity permanently. During the period of transition, the underlying uncertainty might put an established agreement on the management of the stock among the coastal states at risk, as the shift in bargaining power of a coastal state might entice it to prove its claim to a higher share by severely increasing its fishing effort and thus its catches, in order to establish rights to the fishery and gain acceptance for its new status. The other coastal state might try

to limit the other's profit by increasing its fishing effort too. If this transient period lasts for a long time and the noncooperative behavior is allowed to continue, it might threaten the fishery, as the stock cannot sustain a too high fishing mortality indefinitely without either becoming extinct or being driven to the break-even stock level (the level at which further fishing becomes unprofitable). The initial terms of the agreement might no longer be incentive compatible to participating countries in the new environment. If so, renegotiation of the initial agreement is necessary.

As Kaitala and Lindroos (2004) point out, the timing of international agreements can either facilitate or destabilize cooperation. The costs players face, and how players in the game perceive the size of the stock biomass, among other variables, can affect whether or not and when they choose to cooperate (Kaitala and Lindroos 2004). The issue of resilience to shocks in the system in the cooperative solution was raised by Kaitala and Pohjola (1988) and reiterated by Munro (1990). However, it has not yet been tackled either in theory or in practice (Munro 2008). Deterministic models, such as Kaitala and Pohjola (1988), illustrate how changes in the system can lead to an unstable equilibrium. Game-theoretic stochastic models, such as those developed in Sumaila (2002), Laukkanen (2003), and McKelvey et al. (2003), are insightful and can help policy makers anticipate how shocks in the system may effect the cooperative solution (Bailey et al. 2010). However, practical evidence suggests that predicting these shocks is difficult, both in magnitude and direction (Munro 2008). An attempt to better use dynamic modeling in bio-economic and game-theoretic applications should also help to address timing and resilience in cooperative solutions, as could better use of stage games (Bailey et al. 2010).

Conventional dynamic optimization and the time-inconsistency of open-loop game approaches, used broadly in fishery and environmental economics modeling, are inadequate to address the above issue. On the other hand, closed-loop games are appropriate modeling approaches to economic-environmental problems. Nevertheless, closed-loop solutions are often computationally intractable. They are seldom used in

empirical modeling and policy analysis.

Yang (2003) “proposes an algorithm to obtain a closed-loop Nash equilibrium to a [transboundary pollution problem] as a sequence of open-loop Nash equilibria. The approach is illustrated with the RICE model [Nordhaus and Yang 1996] and the policy and methodological implications of the closed-loop strategies are discussed. It is worth noting that this approach is especially useful when the differential game model is intractable and the negotiation rules have a clause allowing for periodical reevaluation of strategies.” (Jørgensen et al. 2010, p. 451).

In this paper, following Yang (2003), we compute closed-loop solutions of sharing the NEA cod fishery between Russia and Norway. We overcome the computational difficulties of closed-loop solution by expressing the solution as a series of open-loop equilibrium solutions. This makes the closed-loop solution a feasible approach in empirical modeling.

Given the economic and cultural importance of the fishery to Norway and North-Western Russia, it is not surprising that there exist numerous studies on fishery management in the Barents Sea (Diekert et al. 2010b). Topics range from overall studies of efficiency (Steinshamn 1993; Arnason et al. 2004; Kugarajh et al. 2006) to the impact of climate change (Hannesson 2007b, 2006). The interaction between the different participating fleets is analyzed by Hannesson (1978), Steinshamn (1994), and Sumaila (1997). Closely related, the effects of cannibalism and interspecies competition on optimal harvesting and fleet selection is studied by Armstrong (1999) and Sandal and Steinshamn (2002). Finally, the strategic game between Russia and Norway has been analyzed cooperatively by Armstrong and Flaaten (1991), Armstrong (1994), Hannesson (1997), and non-cooperatively by Diekert et al. (2010a), and Hannesson (2007a).

The plan of the paper is as follows. The next section describes the cod distribution and migrations, followed by a section discussing the some important environmental factors. A fourth section describes the simulations. In the fifth section we present the results, and finally the sixth section concludes the paper. A more detailed description of the model is relegated to the Appendix.

Migrations

The mature part of the Northeast Arctic cod stock migrates to the Norwegian coast early in the year to spawn, mainly to the waters around the Lofoten Islands. The spawning process is over by the end of April, after which the stock migrates back into the Norwegian Sea and the Barents Sea. The eggs and larvae drift with the current towards Spitzbergen and into the Barents Sea. The immature age groups migrates towards the coast of Finnmark (the northernmost part of Norway) early in the year in search for food, migrating back towards Spitzbergen and the Barents Sea as the spawning migration of capelin is over (Figure 1).

The modeling of these migrations is as follows. First, the year is split into two parts, the first four months and the rest. The mature part of the stock is assumed only to be available for Norway in the first period, because of its spawning migration. The immature part of the stock is assumed to be equally available for Norway and Russia in this period. In the second period the spawning stock is assumed to have migrated back into the Norwegian Sea and the Barents Sea and to be equally available for both countries. The share of the stock available in each country's economic zone varies from year to year, according to climatic conditions, and it is possible that more than half of the stock is available in the Norwegian zone on average, but here we shall assume an even distribution between the zones as a base case.

The spawning stock biomass is determined as the stock remaining half way through the first fishing season (the spawning season), because all fish do not spawn at the same time, and assuming they all do so at the beginning of the period would ensure the survival of the stock even if the spawning stock would be wiped out almost immediately at the beginning of the period.

The location of the spawning grounds is influenced by the climatic conditions such that the center of gravity moves northward with increasing temperature. Furthermore, evidence suggest that the center of gravity of the distribution of young cod has moved

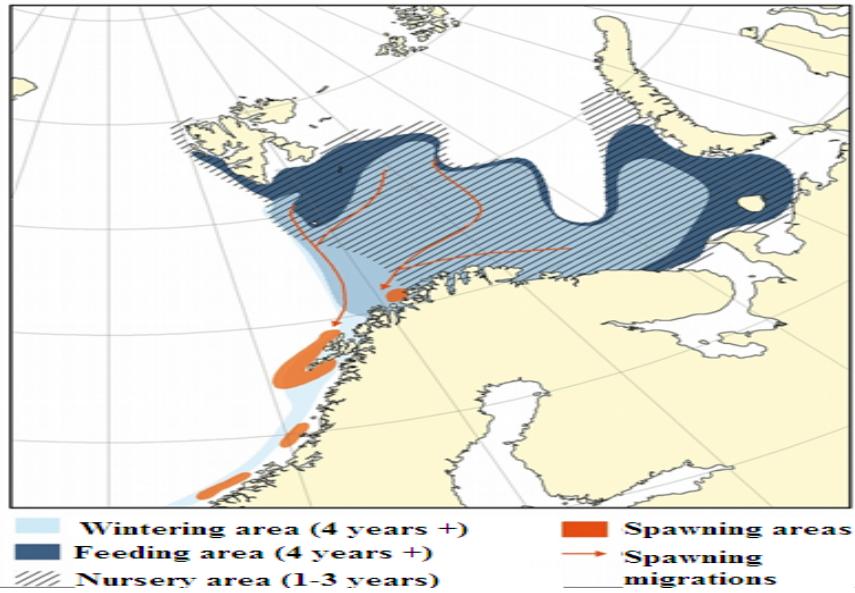


Figure 1: The general distribution of the Northeast Arctic cod. Source: Institute of Marine Research, PO Box 1870 Nordnes N-5817 Bergen, Norway.

eastward since the early 1980s.

One possible effect of a warmer ocean climate is that the cod stock would migrate further north and east into the Barents Sea without necessarily getting any bigger or establishing new spawning areas off the coast of Russia. This would mean that more of the stock would be available in the Russian economic zone.

Environmental conditions

The Barents Sea is one of the world's richest, purest, and most productive marine areas, and where the climate, both in the sea and the atmosphere, is expected to change in response to global warming (ACIA 2004; Stenevik and Sundby 2007; Ellingsen et al. 2008).

However, there is considerable uncertainty about the realization of the above scenario. Simulations show that there will be no change in the decadal mean flow of water into the Barents Sea during the next 50 years, but the temperature of the water transported into the Barents Sea will become significantly higher (increase of about 1°C during the

period) (Ellingsen et al. 2008). Even though the simulation results show that the future climate will be warmer, there are also years when the climate is comparable to periods of the present climate. The position of the Polar Front in the Barents Sea, separating the warm Atlantic water from the cold Arctic water, is strongly governed by topography in the western part of the Barents Sea. In the east, where the topographic control is weak, changes of the position of the Polar Front towards the north and east are more likely (ACIA 2004).

Recruitment levels of individual cod stocks have frequently been associated with variations in temperature during the first year of life. The sign of the relationship between sea surface temperature and recruitment, in the North Atlantic, was generally positive for cold-water stocks (adults which inhabit bottom temperatures $\leq 6^{\circ}C$) and negative for warm-water stocks (adults which inhabit bottom temperatures $\geq 9^{\circ}C$). Stocks in the mid-range of bottom temperatures ($7 - 8^{\circ}C$) tended to have little or no relationship between sea surface temperature and recruitment (Drinkwater 2005)

The copepod *Calanus finmarchicus* is the dominant meso-zooplankton in the Subarctic gyre of the northern North Atlantic and the main prey item for the Northeast Arctic cod larvae and juveniles. It is adapted to the spring bloom of the region, with feeding and reproduction during spring and summer, and hibernation at depth during winter. Through advection by the Norwegian Atlantic Current, the *C. finmarchicus* production spills over from the core regions onto the adjacent shelves, e.g. the shelf off Norway and the Barents Sea (Vikebø et al. 2005). Therefore, Sundby (2000) suggested that the recruitment–temperature relationship for the Northeast Atlantic cod (a cold-water stock) is a proxy for the food abundance during the early stages, explained by the advection of warm *C. finmarchicus*-rich waters from the core production regions to the habitat of cod.

Figure 2 shows the temperature in the Russian Kola Section since 1900. We observe large year-to-year fluctuations. The difference between the warmest and the coldest year is as much as $2^{\circ}C$, which is a lot in this area. Averaging over several years we find what seems

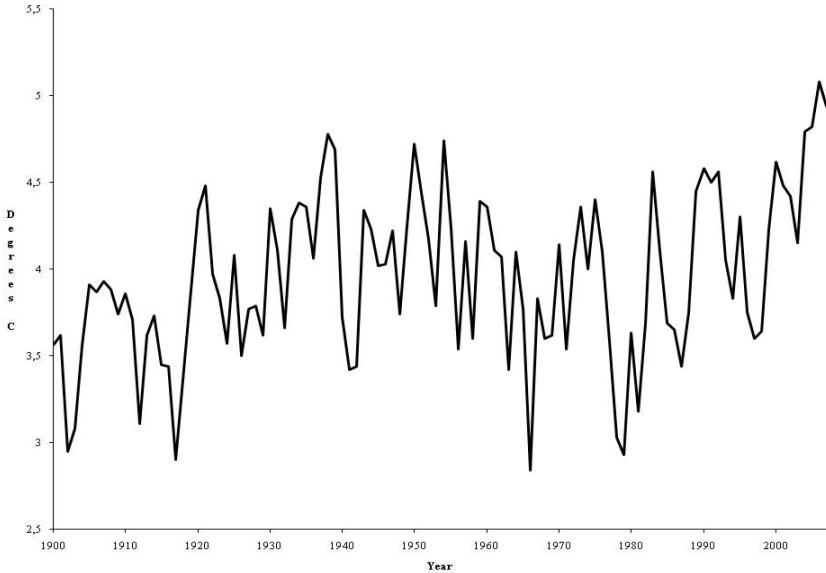


Figure 2: Average annual temperature, Kola Section 1900-2007. No. of obs. = 108, mean temperature = 3.95° C, standard deviation = 0.477, minimum temperature 2.84° C and maximum temperature = 5.08° C. Source: PINRO, Murmansk.

to be periodically fluctuations in the system. Averaging over 30 years, the temperature increased from the beginning of the century until about 1940, and then declined again. The minimum was reached in the late 1970s, and since then the temperature has increased until present. The latter coincides well with other observations that indicates a relative warming the last 30 years (Loeng and Ingvaldsen 2002).

Simulations

Our goal with this work is to simulate how an increase in the productivity of the North-East Arctic cod stock would affect the Russian-Norwegian cooperation on the management of the stock. A productivity increase is linked to environmental conditions in the sea and to climate change through a temperature dependent stock-recruitment relationship of the Ricker-type (see Appendix, Equation A-3), *i.e.*, the number of recruits is positively related to the sea temperature given the spawning stock biomass.

The temperature is measured in degrees Celsius. Although Figure 2 indicated an

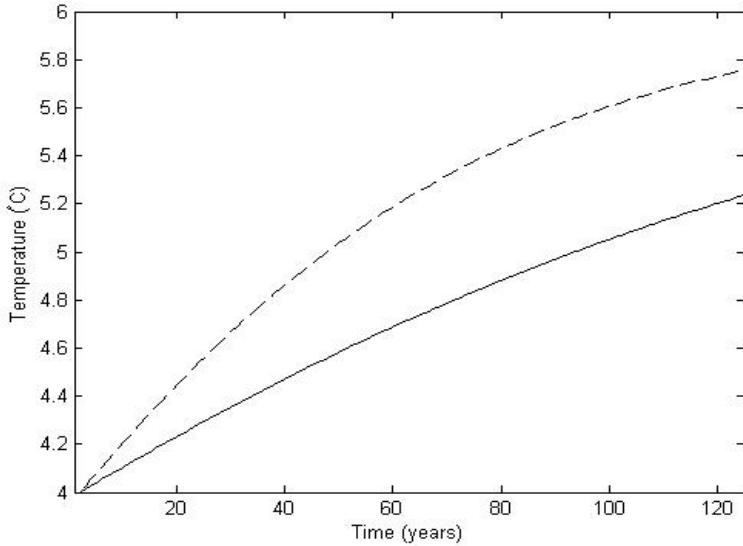


Figure 3: Temperature projection. $\tau_0 = 4$, $\tau_{max} = 6$, and $\mu = 0.01$ (solid) and $\mu = 0.02$ (dashed), respectively.

increase in the sea temperature over the last 30 years there have been considerable fluctuations and care should be taken when we want project temperature development. Firstly, a positive relationship between temperature and recruitment can only be relied upon within the range of the observed temperatures. Beyond these limits we cannot say what will happen. Secondly, the temperature increase during the next 100 years is expected to be in the range of 1-2°C, with considerable annually variation. With this in mind we need to control and keep our simulations of the future temperatures within these limits. Therefore, the temperature change is described by a logistic function

$$\tau_t = \frac{\tau_{max}}{[(\tau_{max} - \tau_0)/\tau_0] \times \exp(-\mu(t - t_0)) + 1},$$

where τ_t is the temperature at time t , τ_{max} is the upper limit temperature, τ_0 is the initial temperature, and μ is the rate of temperature change.

Figure 3 illustrates two different possible temperature development paths, designed to keep the temperature between 4 and 6°C: one with a slower temperature change implied ($\mu = 0.01$) and the other with a more rapid temperature change path ($\mu = 0.02$).

We assume that the two parties, Russia and Norway, maximize the net present values (NPV) from their cod fisheries. Their strategies involve setting the appropriate levels of fishing effort for the fisheries. Norway has two strategic variables, f^{N_a} and f^{N_b} . f^{N_a} is the fishing effort for the mature stock in the first part of the year, which is only available in the Norwegian economic zone because of the spawning migrations. f^{N_b} is the fishing effort for the rest of the stock that is available in its zone the first part of the year, and for the whole stock available in the Norwegian zone in the second part of the year. Russia, however, has only one strategic variable, f^R , which is the fishing effort generating the fishing mortality of the stock available in the Russian zone in both parts of the year, which excludes the spawning part of the stock in the first part of the year.

The noncooperative NPV evaluated at time t will then be contrasted to the results from optimal harvesting (soleowner). The soleowner controls both fleets and, thus, has available the same strategic opportunities as Norway. At the beginning of each stage (t) the respective noncooperative NPVs and the cooperative NPV are calculated, and the players harvest the stock cooperatively in the current stage if the soleowner NPV is as least as great as the sum of their individual noncooperative NPV. If not, they will each carry out the strategy that maximize their individual noncooperative NPV. This calculation and decision process is carried out at the beginning of every stage.

The problem of the soleowner will then be:

$$\max_{f_t} \sum_{t=0}^T \delta^t [\Pi^R(X_t, f_t^R, f_t^N) + \Pi^N(X_t, f_t^R, f_t^N)] \quad (1)$$

subject to the biological system X_t and control f_t .¹

The soleowner controls both fleets. The model is solved for $T = 125$. The long time horizon and discounting, where δ is the discount factor, ensures that the reported solutions will be numerically indistinguishable from the infinite horizon case. The biological system, summarized by X_t , is specified by the vector of biomass with the recruitment function

¹See the Appendix for a more detailed description of the model and its parameters.

(cf. Appendix, Equation A-3) giving the number of three year old fish (recruits) $N_{3,t}$, and the number of fish of age a for $a = 4, \dots, 13+$ according the cohort development $N_{a,t} = N_{a-1,t-1} \times \exp[-q_{a-1} \sum_{i=1}^I f_{t-1}^i - M]$, where $q_a \sum_{i=1}^I f_t^i$ denotes the age-specific fishing mortality F_a , and M is the natural mortality.² q_a is the age-specific catchability coefficients, presented in Table A-2 in the Appendix along with the weight and maturity parameters. As a short hand notation, the system is written as $X_{t+1} = \psi(X_t, f_t^R, f_t^N)$ for $t = t-3, t-2, t-1, t$. The initial state X_0 is given by the assessment of ICES (2008).

A discrete time differential game will be applied, which is described by

- The number of players: Russia and Norway $i = R, N$.
- The number of stages $t = \{0, 1, \dots, T\}$.
- The control variable f^i of player i .
- The state $X_{t+1} = \psi(X_t, f_t^R, f_t^N)$ describing the biological system.
- The pay-off functions of the players which are for Russia and Norway, respectively:

$$J^R = \sum_{t=0}^T \delta^t \Pi^R(X_t, f_t^R, f_t^N)$$

$$J^N = \sum_{t=0}^T \delta^t \Pi^N(X_t, f_t^R, f_t^N)$$

Each agent will choose a strategy which maximizes his NPV. The choice of player i will therefore be a best response to the strategy of player j and the prevailing state. The outcome of this reciprocal optimization will be a situation where no player can improve his pay-off by unilaterally altering his decision. The equilibrium strategies f^{i*} thus satisfy:

$$J^i(X, f^{i*}, f^{j*}) \geq J^i(X, f^i, f^{j*}) \quad \text{for all } X, f, i.$$

²The natural mortality (M) was set at 0.2, which appears to be a common assumption (ICES 2008).

Following Yang (2003), we solve a series of distinctive open-loop strategies in each time period. The closed-loop strategy is the union of segments extracted from these open-loop strategies. More specifically, the method solves the open-loop strategic profiles of agents (countries) starting at $t = 0$ and ending at $t = \infty$ as the first step.³ However, only the decisions that affect the actions in $t = 1$ are placed in the set of closed-loop strategy. When time moves to $t = 1$, the countries will reevaluate their decisions made at $t = 0$. If no new information is available, the countries will abide by their strategies set at $t = 0$. If there is new information and/or shocks at $t = 1$, the countries will restart the open-loop decision process from $t = 1$ to infinity with the new information. In the strategy profile of this new open-loop solution, only actions in $t = 2$ are incorporated into the closed-loop solution. Similar decision processes are repeated at $t = 2, 3, \dots, T, \dots$. The second period in each sequential open-loop decision make up the closed-loop strategic profiles.

The problem has been solved numerically for the soleowner optimization and the noncooperative game using the MATLAB optimization toolbox. Similarly to the adjustment process in the standard Cournot game, the process of iteratively updating the best responses lets the players' strategies converge to the open-loop equilibrium paths. The procedure finds the open-loop solutions in 10 iterations or less. The robustness of this procedure is tested in the following way. We execute the sequential procedure without temperature change. Without any update of new information the closed-loop solution should equal the open-loop solution. As the outcome is identical to the conventional open-loop solution, the solution is time-consistent in the sense that it constitutes a Nash equilibrium for every subgame along the equilibrium path. By applying a set of random starting values and changing the sequences of countries in the iterations, the iterative procedure converges to the same Nash equilibrium. To approximate the infinite time horizon problem, we solve each open-loop problem with a long time horizon (125 years with 5% annual rate of discount). With an extended time horizon and discounting, what happens in the terminal time periods has a negligible effect on the trajectories in the first

³A sufficiently large number, instead of ∞ , is used in numerical simulations.

few periods.

Comparison between the different NPVs will be carried out in the following way. The ratio between the noncooperative NPVs and the soleowner NPV is the criteria that decides if the countries will engage in cooperation or not. If the sum of Norway's and Russia's noncooperative NPVs divided by the soleowner's NPV is less than 1, the countries choose to cooperate. If this ratio is equal to 1 (but for deviations in the order of one per mille, which are attributable to numeric imprecision), there will be no cooperation in this period. We call this ratio the joint threat point.

Generally, a single player cannot achieve an NPV equal to a soleowner, unless he himself is a soleowner. In the North-East Arctic fishery, where Norway and the "soleowner" has two strategic variables, f^{N_a} and f^{N_b} , and Russia has only one strategic variable, f^R , Norway can obtain an NPV equal to the optimal soleowner NPV without cooperation from Russia, if it is optimal to only harvest the mature part of the stock during the spawning season and Russia finds a positive level of f^R unprofitable, leaving the remaining stock unharvested the rest of the year.

The results from optimal harvesting (soleowner) will be contrasted to (i) a game of two players which control their own annual harvesting, but are unable to make binding agreements. Additionally, (ii) a game where one of the players can control its own harvesting by choosing a separate effort level to be applied to the spawning stock during the spawning season, while the other player only can control its overall annual harvest, will be simulated.

Results

Figures 4-15 display the temporal development in (a) the threat points, (b) the materialized fishing effort, either cooperative or noncooperative, and the effective fishing mortality, (c) the harvest, either cooperative or noncooperative, and (d) total and

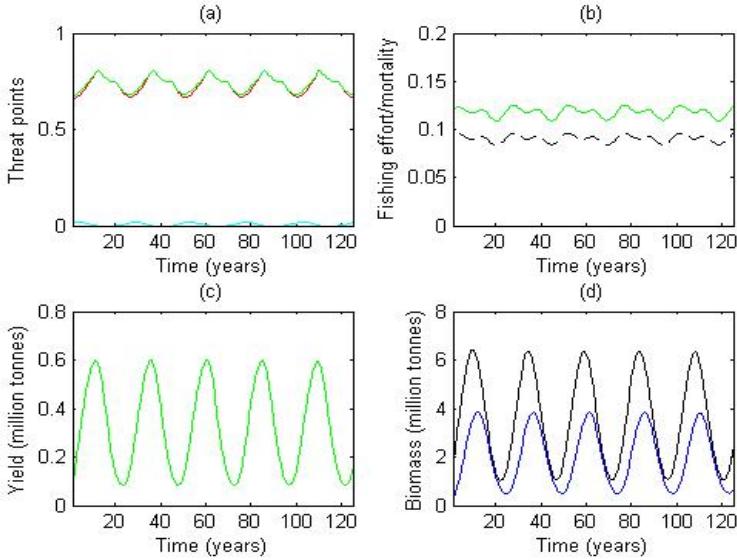


Figure 4: A single annual strategic variable for all. Variable costs and constant temperature. Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

spawning stock biomass.⁴

(i) A single annual strategic variable for all

Figures 4-6 display the temporal development, where both Russia and Norway, and the soleowner, are assumed only to be able to control their annual effort levels and are unable to separate the effort applied to the mature part of the stock during the spawning migrations from the effort applied to the remaining stock during and after the spawning season.

Figure 4 shows the development over time without temperature change. Figure 4 (a) shows the joint threat points, as well as the individual countries, noncooperative profits as shares of the optimal cooperative profit. We see that the joint threat point always is less than 1, meaning that both Norway and Russia would be better off cooperating than not over the entire simulation period. The optimal soleowner NPV is sufficiently large

⁴Norwegian and Russian fishing refers to their noncooperative game solutions. Otherwise, when they do cooperate, they partake in the soleowner's fishery, where a distribution of the harvest is unspecified.

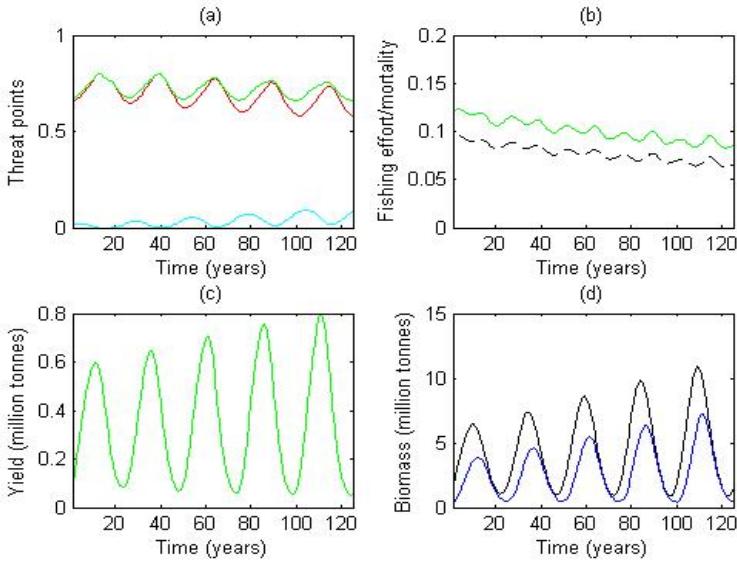


Figure 5: A single annual strategic variable for all. Variable costs, increasing temperature ($\mu = 0.01$). Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

to cover both Russia's and Norway's noncooperative NPVs, jointly. In addition, because the joint threat points are substantially less than 1, there are profits in excess of the joint noncooperative NPVs to be shared. However, we do not assume any sharing rules for the excess profit, but concentrate on the incentives for cooperation.

The threat points appear to be fluctuating over time. Figure 4 (b) shows that the implied fishing mortalities (F) rarely are above 0.1. With low levels of F the spawning stock biomass will increase, and the recruitment with it, but only up to a certain point. If the spawning biomass increases beyond this point the recruitment will fall and eventually the (spawning) biomass will start to decline. When the spawning biomass again enters the interval where there is a positive relationship between the spawning stock size and the number of recruits entering the fishery three years after spawning the decline in biomass will stop, and the entire process will repeat itself. This explains the fluctuations in the threat points, fishing efforts and mortalities, harvest and biomass. They will vary depending on the current stage of this process. Under noncooperation, Russia would from time to time abstain from fishing, displaying a pattern of pulse fishing (Figure 4 a).

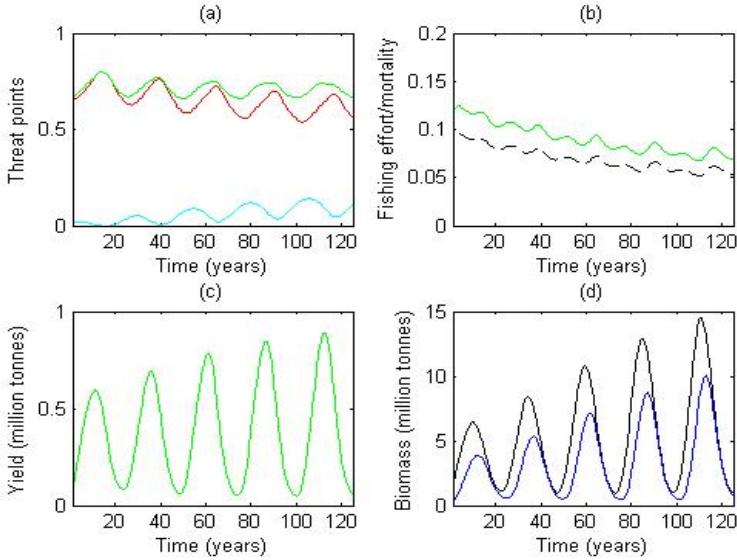


Figure 6: A single annual strategic variable for all. Variable costs, increasing temperature ($\mu = 0.02$). Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

Figure 5 and 6 shows the development over time, where we assume (5) a relatively slow and (6) a more rapid temperature increase, respectively. We see that cooperation always is preferred over noncooperation, and that there are fluctuations in the harvest and biomass caused by the stock dynamics, given by the stock-recruitment relationship. The amplitude of the fluctuations appears to be increasing with the temperature. Although the maximum harvest and biomass levels increases with higher temperature the minimum levels do not change. In spite of the increased volatility, Russia's tendency towards pulse fishing appears to be reduced as the temperature increases. Notice that the optimal fishing effort and F falls over time when the temperature increases. This can be explained by the inverse relationship between the price and the quantity of landed fish (Appendix, Equation A-7) and the positive relationship between effort and costs (Appendix, Equation A-6). When the productivity of the stock increases the catch per unit of effort increases, meaning that, *ceteris paribus*, the price will decline. To compensate for the decline in price per quantity landed, it is optimal to lower the costs by reducing the fishing effort, and indirectly reduce the fishing mortality.

(ii) Norway and soleowner have two annual strategic variables, Russia one.

Figures 7-9 display the temporal development, where Norway, and the soleowner can control their own harvesting by choosing an effort level to be applied to the spawning stock during the spawning season that is different from the effort level applied to the immature part of the stock during the spawning migrations as well as the remaining stock during and after the spawning season. For Russia, on the other hand, only the latter is possible. As it turns out, Norway, and the soleowner, only wish to fish the mature part of the stock. One reason for this lies in the greater selectivity this affords of mature age groups; fishing these age groups selectively better utilizes the growth potential of the stock (Hannesson 2006, p. 642). Another reason, and why it might still be profitable for Norway to continue harvesting only the mature stock while Russia harvests both the mature and the immature stock, is that harvesting the mature stock exclusively is only possible in one third of the year, reducing the effort-dependent costs by one third.

Figure 7 shows the case without temperature change. Now we see that the threat point occasionally is equal to 1. As in the previous cases, under noncooperation, Russia sometimes would find it profitable to abstain from harvesting, leaving the fishery to Norway alone. In that case Norway's profit is identical to soleowner profit, because both Norway and the soleowner will only fish when they are able to target the mature part of the stock exclusively, when Russia chooses not to fish. Norway, in effect, becomes a soleowner. However, this is a pulse fishing strategy, and when Russia again finds it profitable to fish, Norway's soleowner advantage is gone. Russia's pulse fishing behavior and the fluctuation in the results comes from the fact that at low levels of fishing mortalities the spawning stock biomass, and therefore the recruitment, varies over time. There is no steady state. When Russia finds fishing profitable under noncooperation, Norway, as well as Russia, prefers cooperation over noncooperation.

In the cases of temperature change (Figures 8 and 9), Russia's strategy of pulse fishing

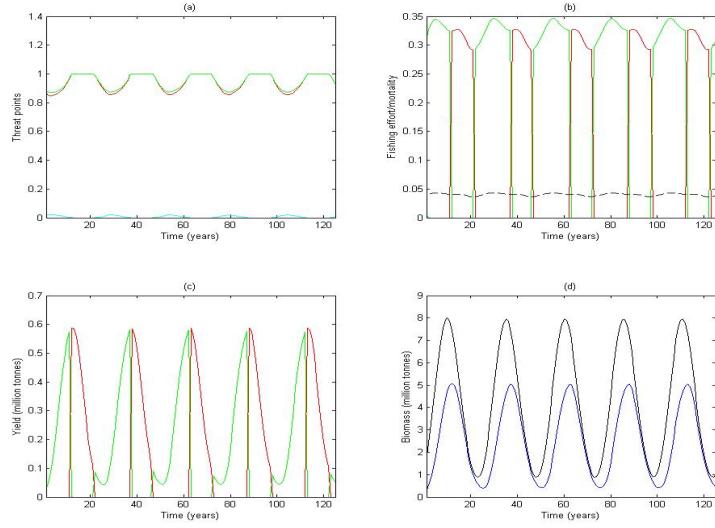


Figure 7: Norway and soleowner have two annual strategic variables, Russia one. Variable costs, constant temperature. Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue). Strategy f^a : solid, and strategy f^b : dash-dot.

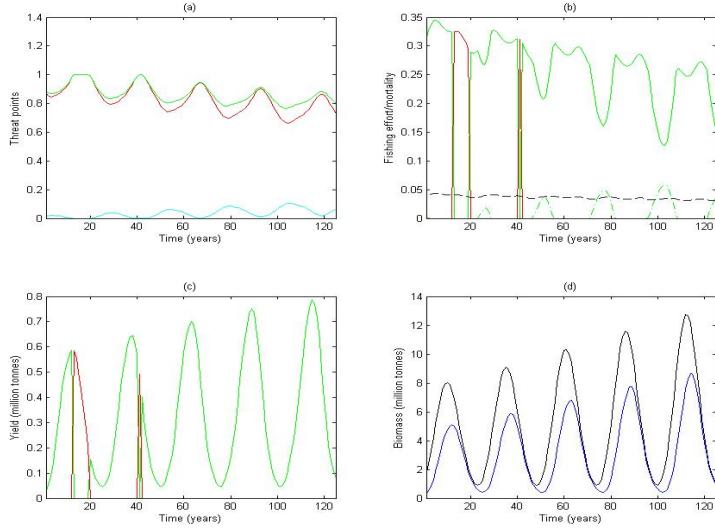


Figure 8: Norway and soleowner have two annual strategic variables, Russia one. Variable costs, increasing temperature ($\mu = 0.01$). Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue). Strategy f^a : solid, and strategy f^b : dash-dot.

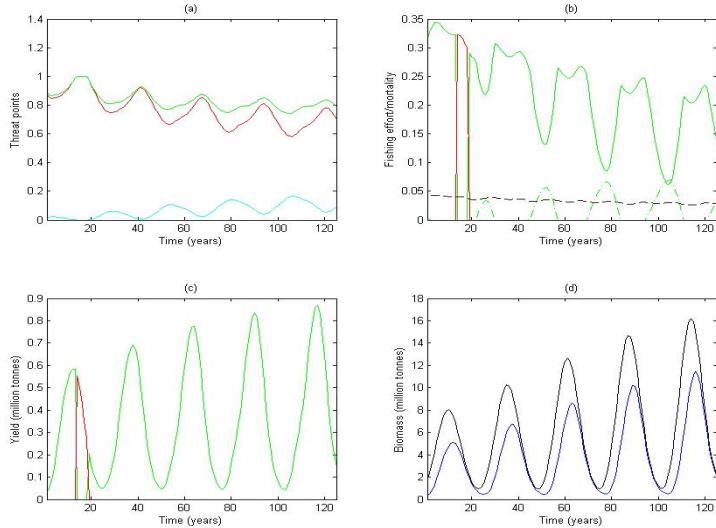


Figure 9: Norway and soleowner have two annual strategic variables, Russia one. Variable costs, increasing temperature ($\mu = 0.02$). Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue). Strategy f^a : solid, and strategy f^b : dash-dot.

becomes less important, and in effect only occurs in the early stages of the simulation period. As with no temperature increase, cooperation is only partially the most profitable strategy for both countries. However, as temperature and productivity increases, the duration of the cooperative periods becomes longer; in the case with the slowest change (Figure 8) cooperation appears to become permanent after 40 years, while with the more rapid temperature change (Figure 9) cooperation becomes permanent after only 20 years.

The implied fishing effort appears to be quite high, although the fishing mortality is fairly low. The reason is that when Norway and the soleowner choose a positive value for strategy f^a , while holding the strategy f^b equal to zero, the effort is only applied to catching mature fish for one-third of the year and thus the low fishing mortality. The practical relevance of this is limited because it would imply harvesting only during the first third of the year. Concentrating the catches to the first part of the year would be less attractive because of the pressure it puts on prices, either by a glut in the fresh fish market or by large and costly processing capacity necessary to cope with seasonal

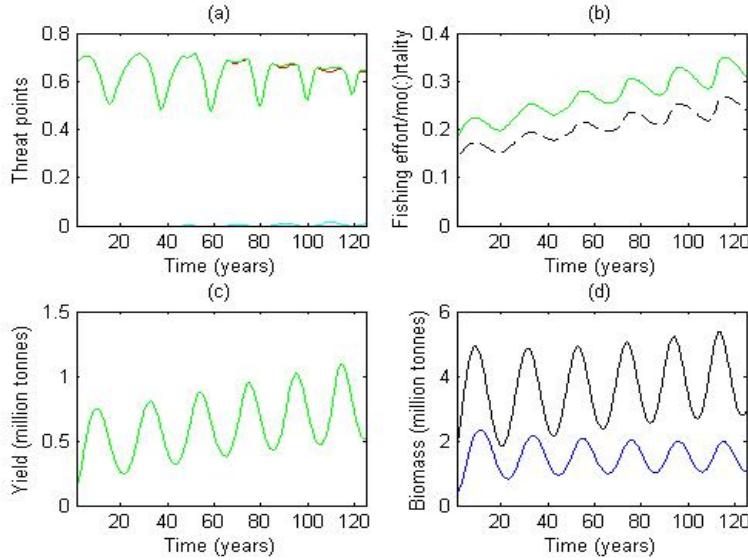


Figure 10: A single annual strategic variable for all. Variable costs, increasing temperature ($\mu = 0.01$), and a constant price = NOK 14 kg^{-1} . Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

supplies of raw fish (Hannesson 2006).

However, from Figures 8 and 9 we see that the soleowner occasionally finds it profitable to harvest the whole stock the entire year. The f^a is sometimes reduced in favor of f^b . Interestingly, this happens when the spawning stock biomass is at its lowest. Then the soleowner finds it profitable to reduce the fishing mortality of the mature part of the stock, and direct some of the effort towards catching immature fish during the spawning season, as well as both mature and immature the remainder of the year.

Sensitivity analysis

As noted, the optimal fishing effort decreases as the temperature increases. This was explained by the inverse relationship between the price of fish and the total quantity of fish landed, whereas the costs are positively related to the fishing effort. The sensitivity of the outcomes was tested for fixed prices of 14 and 17 NOK kg^{-1} at a rate of temperature change $\mu = 0.01$.

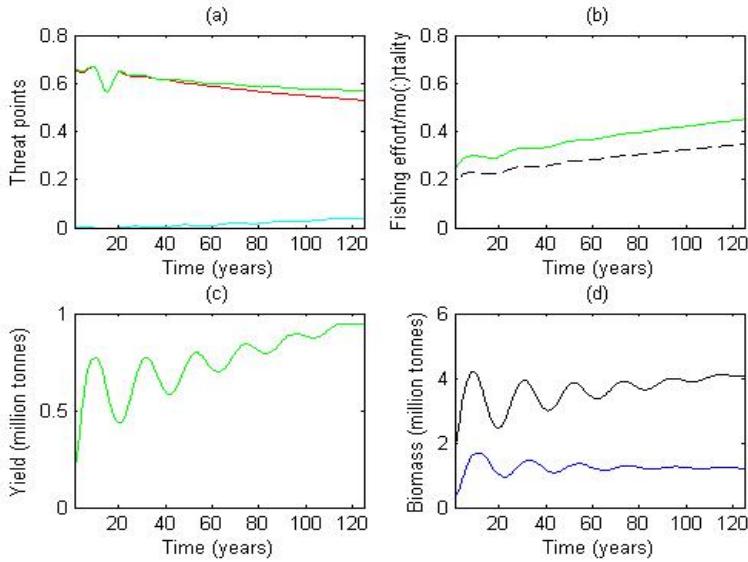


Figure 11: A single annual strategic variable for all. Variable costs, increasing temperature ($\mu = 0.01$), and a constant price = NOK 17 kg^{-1} . Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

Figures 10 and 11 shows the development over time for prices 14 and 17 NOK kg^{-1} , respectively, where both Russia and Norway, and the soleowner are assumed only to be able to control their annual effort levels and are unable to separate the effort applied to the mature part of the stock during the spawning migrations from the effort applied to the remaining stock during and after the spawning season.

Now we see that the fishing effort and fishing mortality increases over time with the temperature. The increasing F has the effect that fluctuations in yield and biomass are more dampened than with a price that depends on the quantity landed. In particular, when the price is equal to 17 (Figure 11), the levels of yield, stock biomass and spawning biomass approach a steady state as temperature increases. The reason for this is that at F above 0.2 the fishing mortality is so high that the biomass stops increasing beyond the level where recruitment is reduced.

Figures 12 and 13 shows the development over time for prices 14 and 17 NOK kg^{-1} , respectively, where Norway and the soleowner can control their own harvesting

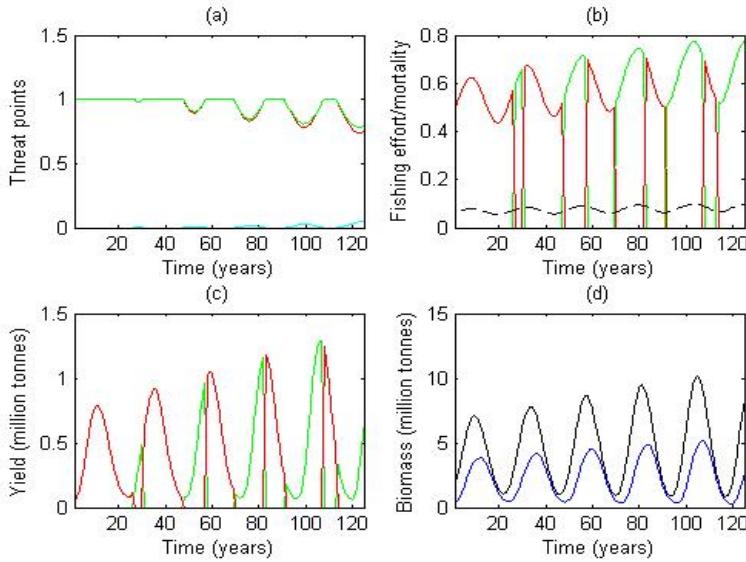


Figure 12: Norway and soleowner have two annual strategic variables, Russia one. Variable costs, increasing temperature ($\mu = 0.01$), and a constant price = NOK $14\ kg^{-1}$. Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue). Strategy f^a : solid, and strategy f^b : dash-dot.

by choosing an effort level to be applied to the spawning stock during the spawning season different from the effort level applied to the immature part of the stock during the spawning migrations as well as the remaining stock during and after the spawning season. Russia, on the other hand, only the latter is possible.

Holding the price fixed results in increasing fishing effort as the temperature increases. The fishing mortality F , however, does not increase, and stays fairly low. The reason for this is the pattern of harvest. Because it is optimal to only harvest the mature part of the stock during the spawning season, the implied fishing mortality only applies to the mature fraction of the stock a third of the year, making the actual yearly F smaller. We do not observe the same dampening effect on yield and biomass as in Figures 10 and 11.

However, we observe in the low price case (Figure 12) that it starts with noncooperation, mainly because of Russia's low activity, followed by alternating cooperation and noncooperation. In contrast, the high price case, Figure 13, begins with alternating cooperation and noncooperation that turns into permanent cooperation

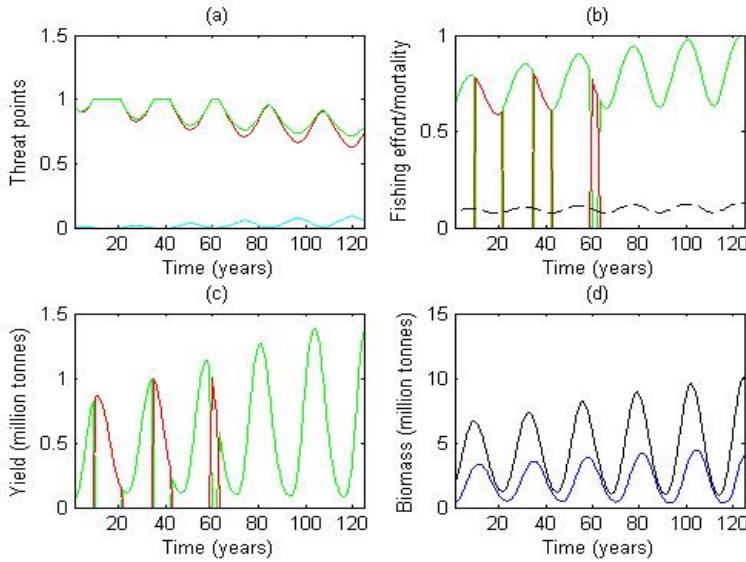


Figure 13: Norway and soleowner have two annual strategic variables, Russia one. Variable costs, increasing temperature ($\mu = 0.01$), and a constant price = NOK 17 kg^{-1} . Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue). Strategy f^a : solid, and strategy f^b : dash-dot.

after about 60 years, not unlike what we observe with quantity dependent price (Figure 8). We do not, however, observe any mixed strategies with regard to harvest of the both the mature and immature parts of the stock throughout the year.

Recall that Russia and Norway each had access to one half of the stock, except for the spawning stock during the spawning season, in their respective zones. If we relax this assumption and allow Russia access to more than on half of the stock, then Norway in some cases might always prefer the cooperative solution over the noncooperative one. An example of this is shown in Figure 14, where Russia has access to $2/3$ of the stock in its zone, whereas Norway has sole access to the spawning stock during the spawning season but has only access to $1/3$ of the remaining stock. In the noncooperative game, Russia would always have positive fishing effort. Regarding the cooperative solution, this is now always preferred over the noncooperative, for both Norway and Russia. This is in contrast to Figure 7, where Russia in the noncooperative game from time to time found it optimal to refrain from harvesting, enabling Norway to reap the soleowner profit

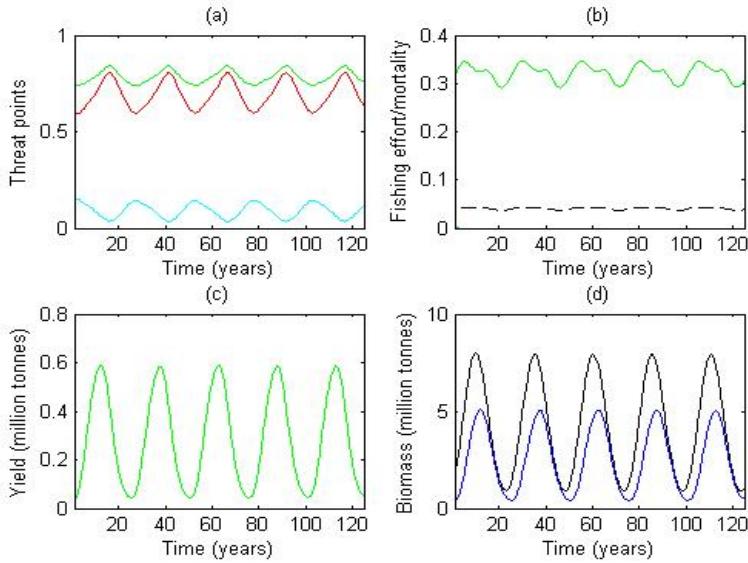


Figure 14: Norway and the soleowner can control their own harvesting by choosing an effort level to be applied to the spawning stock during the spawning season different from the effort level applied to the immature part of the stock during the spawning migrations as well as the remaining stock during and after the spawning season. Russia, on the other hand, only the latter is possible. Russia has access to 2/3 of the stock in its zone, whereas Norway has sole access to the spawning stock during the spawning season but has only access to 1/3 of the remaining stock. Variable costs, constant temperature. Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

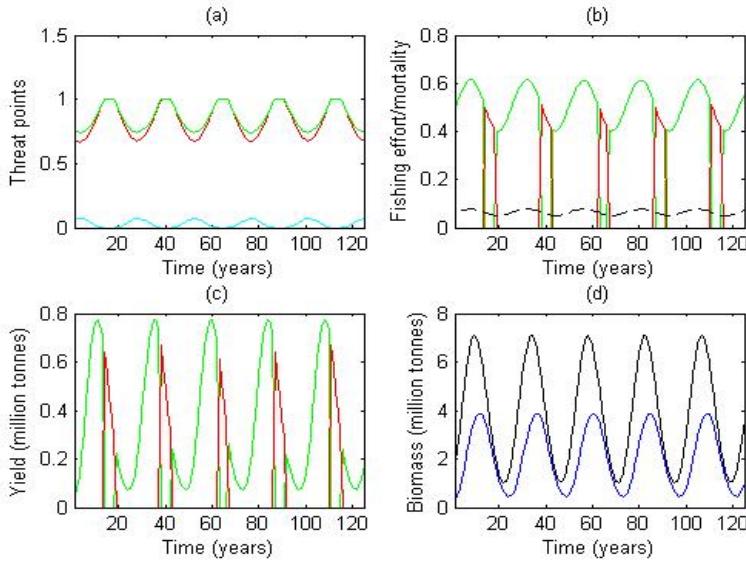


Figure 15: Norway and the soleowner can control their own harvesting by choosing an effort level to be applied to the spawning stock during the spawning season different from the effort level applied to the immature part of the stock during the spawning migrations as well as the remaining stock during and after the spawning season. Russia, on the other hand, only the latter is possible. Russia has access to $2/3$ of the stock in its zone, whereas Norway has sole access to the spawning stock during the spawning season but has only access to $1/3$ of the remaining stock. Variable costs, constant temperature, and a constant price = NOK $14\ kg^{-1}$. Soleowner (green), Norway (red), Russia (cyan), fishing mortality (dashed), total stock biomass (black), and spawning stock biomass (blue).

for itself.

The variations in recruitment, yield and biomass depends on the level of the fishing mortality F . If F is low (below 0.2, cf. Appendix, Figure A-2) there is now single level of sustainable yield, spawning stock biomass or total stock biomass. The reason for this is the fluctuating recruitment. because at low levels of F there will be surplus growth and the (spawning) biomass will increase over time. Eventually, the biomass becomes so large that it starts to have a negative effect on the recruitment. After some time, as a result of the falling recruitment, the biomass starts to decline. When the biomass again enters the size interval where there is a positive relationship between the spawning stock biomass and recruitment the process repeats itself. The variations in yield and biomass are driven by the intrinsic stock dynamics, governed by the stock-recruitment function.

Table 1: A single annual strategic variable for all. Present values (2007 millions NOK) in different scenarios and strategic settings.

	$\mu = 0$	$\mu = 0.01$	$\mu = 0.02$
Reevaluation			
Soleowner	63363	65847	67725
Noncooperation			
Russia	614.5	894.0	1373.9
Norway	44624	45366	45591
Total	45239	46260	46965

As the results shows, F is fairly low and relatively stable. Facing a relatively high fixed price (NOK 17 kg^{-1}) and a temperature increase we see that F increases, moving towards a “steady state”. At a relatively low fixed price (NOK 14 kg^{-1}), on the other hand, F is fairly low and the recruitment, yield and biomass continue to fluctuate. Figure 15 illustrate the latter in the case where Russia has access to $2/3$ of the stock in its zone, whereas Norway has sole access to the spawning stock during the spawning season, but has only access to $1/3$ of the remaining stock. The possibility of temporarily break of cooperation is present, even if Russia has access to a larger share of the stock.

Summary and comparison of results

Tables 1 and 2 summarize the results in Figures 4-6 and Figures 7-9, respectively, displayed as the equilibrium path’s present values evaluated today. By reevaluation we mean, as in Figures 4-9, that the countries are able to reevaluate whether or not to cooperate at the beginning of every period. On the other hand, by noncooperation we mean the present value of no cooperation at all. Finally, soleowner tells us the present value of full cooperation.

We see that the gains from cooperation is considerable. Russia, especially, gains the most from cooperation, as its net present values when not cooperating is probably not large enough to cover the fixed costs.

Table 2: Norway and soleowner have two annual strategic variables, Russia one. Present values (2007 millions NOK) in different scenarios and strategic settings.

	$\mu = 0$	$\mu = 0.01$	$\mu = 0.02$
Reevaluation			
Cooperation	26017	38398	45009
Russia	1.3	0.07	0
Norway	25832	15811	11001
Total	51850	54210	56010
Noncooperation			
Russia	603.9	941.8	1461.2
Norway	48290	48791	48726
Total	48921	49733	50187
Soleowner	51852	54210	56010

Regarding Table 2, when reevaluation is allowed and the countries cooperate only in those periods where the cooperative profits are large enough to simultaneously cover both countries noncooperative profits, we see that Russia has relatively low present values, probably not large enough to cover the fixed cost. Recall that we do not assume any sharing rules for the optimal profits in excess of the threat points. Therefore, the present values of Russia and Norway, under reevaluation (Table 2), are the values of their own profit in those periods when cooperation breaks down. Russia would gain more from cooperation than Norway, and would have preferred to cooperate more often than Norway. Turning to the noncooperative solutions there is considerable loss involved, even compared to the reevaluation case. Russia's present values are all fairly low and the total present values are much reduced compared to the previous case. Moreover, the soleowner's present values are significantly higher than the total present values in the noncooperative cases.

If we compare the soleowner's present values in Tables 1 with 2, the values are significantly higher in the former compared to the latter. It is more profitable for a soleowner to apply a single annual effort level on the entire stock, than sometimes only harvest the mature stock during the spawning season and other times harvest the entire

stock the whole year. However, if we compare the noncooperative present values looking at the countries' present values the opposite is true. The values in Table 2 are higher than the ones in Table 1 and significantly so in Norway's case. Although the case where both Norway and a soleowner have two annual strategic variables, and Russia only one, can be criticized for being unrealistic or unpractically, the fact that Norway would prefer this strategy over the alternative of harvesting the entire stock with an uniform effort throughout the year, raises Norway's share in the cooperative profit and enhances its bargaining position versus Russia.

Discussion and conclusion

We simulate how an increase in the productivity of the North-East Arctic cod stock would affect the Russian-Norwegian cooperation on the management of the stock. Furthermore, we performed the simulations under two different assumption about the strategic variable available for Norway and the soleowner: (i) a single annual effort level, and (ii) one effort level applied to the mature part of the stock during the spawning season, and another effort level for the immature part of the stock during the spawning and the remaining total stock the rest the year. With spawning exclusively taking place in Norwegian waters, Russia have only option (i) available.

The results showed that in (i) cooperation is always preferred over noncooperation. This is as expected. A single player cannot achieve as much profit as a soleowner. A soleowner would maximize profit by harvesting the fish in its entire distribution area, throughout the year, and even if Norway would continue to fish noncooperatively while Russia in some time periods finds it better not to fish, Norway would be restricted to fish only on the fraction of the stock available in its own waters.

However, in (ii) the strategy that maximizes the soleowner profit is to fish the mature part of the stock during the spawning season only, and for the remaining year leaving the rest of the stock, and what is left of the spawning stock, unfished. Under

noncooperation, this means that when Russia, from time to time, is better off not fishing, Norway, which controls the spawning areas, can earn the maximum soleowner profit for itself by applying the same strategy as the soleowner, without the cooperation of Russia. When this happens, there is of course no basis for a cooperative agreement. This may seem trivial, considering that the economic loss is negligible if we compare the total NVPs from reevaluation with the soleowner NPVs (Table 2). Moreover, as pointed out in the introduction, the climate change phenomenon and its effects is not a straightforward process, and that considerable time might pass before its consequences is fully acknowledged by all parties. Therefore, any disruption of the initial agreement leading to a collapse in cooperation and prolonged periods of competitive behavior might have dire consequences for the stock.

Temperature/productivity increases seem to be favorable for the incentives for cooperation and the stability of an agreement on the joint management of the NEA cod fishery. Again, as discussed earlier, there is the question of the relevance of assumption (ii) regarding the strategic variables. Strategy scenario (i) of fishing the entire stock throughout the year is for various reasons considered the most realistic alternative. However, strategy scenario (ii) might be relevant considering Norway's advantage of being able to target the mature part of the stock separately. If we compare Norway's NPVs under noncooperation in Table 1 with Table 2, we see that Norway's NPV by applying strategy scenario (ii) are higher than the corresponding NPVs in strategy scenario (i). Therefore is it possible that Norway expects a higher share of the cooperative NPV than Russia is willing to accept. This might lead to tension between the two countries trying to reach an agreement.

The result that increased recruitment and productivity of the stock improved stability of an agreement on joint management is what we might expect and is also in line with what Brandt and Kronbak (2010) found to be the case for the management of the Baltic Sea cod. However, the novelty of our approach lies mainly in the application of the method of expressing the closed-loop solution as a series of open-loop equilibrium solutions

(Yang 2003) to overcome the intractability of the temporal problem of whether or not cooperation is stable in a differential fishery game model, and to study the issue of reevaluation international agreements on shared fish stocks. This highlights the need for better and more flexible management systems that can cope with shifting environmental conditions.

The procedure is easily extended to include more players than the rather simple two player game between Norway and Russia. Including more than two players requires the analysis of coalitions taking into account the positive externalities usually present in the management of shared and straddling fish stocks. In fact, as the members of a coalition tend to adopt management strategies conserving the stock, a nonmember is typically better off the greater the number of countries that join the coalition. This is relevant for NEA cod fishery, where Russia and Norway make arrangement for third part countries' fisheries within the TAC. Furthermore, the NEA cod straddles into international waters, where it can be fished in an illegal, unreported and unregulated manner by fishing vessels from any country, not just those approved by Russia and Norway. Allowing for more players and externalities would raise more intricate questions and produce more interesting results.

References

- ACIA 2004. Impacts of a Warming Arctic - Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, UK. <http://www.acia.uaf.edu>.
- Armstrong, C. 1994. Cooperative solutions in a transboundary fishery: The Russian-Norwegian co-management of the Arcto-Norwegian cod stock. *Marine Resource Economics* 9: 329–351.
- Armstrong, C. 1999. Sharing a resource – bioeconomic analysis of an applied allocation rule. *Environmental and Resource Economics* 13(1): 75–94.
- Armstrong, C. and Flaaten, O. 1991. The optimal management of transboundary fish resource—the Arcto-Norwegian cod stock. In *Essays on the Economics of Migratory Fish Stocks. Studies in Contemporary Economics*, edited by R. Arnason and T. Bjørndal, pp. 137–152. Springer Verlag, Berlin.
- Arnason, R., Sandal, L.K., Steinshamn, S.I., and Vestergaard, N. 2004. Optimal feedback controls: comparative evaluaton of the cod fisheries in Denmark, Iceland, and Norway. *American Journal of Agricultural Economics* 86(2): 531–542.
- Bailey, M., Sumaila, U.R., and Lindroos, M. 2010. Application of game theory to fisheries over three decades. *Fisheries Research* 102: 1–8.
- Beverton, R.J.H. and Holt, S.J. 1957. *On the Dynamics of Exploited Fish Populations*. Chapman & Hall, London.
- Brandt, U.S. and Kronbak, L.G. 2010. On the stabilty of fishery agreements under exogeneous change: An example of agreements under climate change. *Fisheries Research* 101: 11–19.
- Diekert, F.K., Hjermann, D.Ø., Nævdal, E., and Stenseth, N.C. 2010a. Non-cooperative exploitation of multi-cohort fisheries - the role of gear selectivity in the North-East Arctic cod fishery. *Resource and Energy Economics* 32: 78–92.

Diekert, F.K., Hjermann, D.Ø., Nævdal, E., and Stenseth, N.C. 2010b. Spare the young fish: Optimal harvesting policies for North-East Arctic cod. *Environmental and Resource Economics* p. 21.

Drinkwater, K.F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. *ICES Journal of Marine Science* 62(7): 1327–1337.

Ekerhovd, N.A. 2010. The stability and resilience of management agreements on climate-sensitive straddling fishery resources: the blue whiting (*Micromesistius poutassou*) coastal state agreement. *Canadian Journal of Fisheries and Aquatic Sciences* 67(3): 534–552.

Ekerhovd, N.A. in preparation. Unpublished data. Samfunns- og Næringslivsforskning AS [SNF, Institute for Research in Economics and Business Administration], Bergen, Norway.

Ellingsen, I.H., Dalpadado, P., Slagstad, D., and Loeng, H. 2008. Impact of climatic change on the biological production in the Barents Sea. *Clim. Change* 87: 155–175.

Fiskeridirektoratet 1998-2007. Lønnsomhetsundersøkelse for fiskeflåten. Helårsdrevne fartøy i størrelsen 8 meter største lengde og over. Fiskeridirektoratet (Directorate of Fisheries), Bergen, Norway.

Hannesson, R. 1978. Trålfiske eller skreifiske? Om optimal beskatning av den norske arktiske torsk. Økonomiske skrifter 12, Department of Economics, University of Bergen, Bergen, Norway.

Hannesson, R. 1997. Fishing as a supergame. *Journal of Environmental Economics and Management* 32: 309–322.

Hannesson, R. 2006. Sharing the Northeast Arctic cod: Possible effects of climate change. *Natural Resource Modeling* 19(4): 633–654.

- Hannesson, R. 2007a. Cheating about the cod. *Marine Policy* 31(6): 698–705.
- Hannesson, R. 2007b. Geographical distribution of fish catches and temperature variations in the Northeast Atlantic since 1945. *Marine Policy* 31(1): 31–39.
- Hannesson, R. 2007c. Global warming and fish migrations. *Natural Resource Modeling* 20(2): 301–319.
- ICES 2008. Report of the Arctic fisheries working group. ICES CM 2008/01:ACOM.
- Jørgensen, S., Martín-Herrán, G., and Zaccour, G. 2010. Dynamic games in the economics and management of pollution. *Environmental Modeling and Assessment* 5(6): 433–467.
- Kaitala, V. and Lindroos, M. 2004. When to ratify an environmental agreement: The case of high seas fisheries. *International Game Theory Review* 6(1): 55–68.
- Kaitala, V. and Pohjola, M. 1988. Optimal recovery of a shared resource stock: A differential game model with efficient memory equilibria. *Natural Resource Modeling* 3: 91–119.
- Kovalev, Y. and Bogstad, B. 2005. Evaluation of maximum long-term yield for Northeast Arctic cod. In *Ecosystem dynamics and optimal long-term harvest in the Barents Sea fisheries. Proceeding of the 11th Russian-Norweian symposium*. Murmansk, 15-17 August 2005, edited by V. Shibanov, pp. 140–159. PINRO Press, Murmansk.
- Kugarajh, K., Sandal, L.K., and Berge, G. 2006. Implementing a stochastic bioeconomic model for the North-East Arctic cod fishery. *Journal of Bioeconomics* 8(1): 35–53.
- Laukkonen, M. 2003. Cooperative and non-cooperative harvesting in a stochastic sequential fishery. *Journal of Environmental Economics and Management* 45: 454–473.
- Loeng, H. and Ingvaldsen, R. 2002. Er det en klimaendring på gang i havet? In *Havets*

miljø 2002. Fisken og havet, særnr. 2-2002, edited by J.H. Fosså, pp. 94–96. IMR, Bergen, Norway.

McKelvey, R., Miller, K., and Golubtsov, P. 2003. Fish wars revisited: a stochastic incomplete-information harvesting game. In Risk and Uncertainty in Environmental and Natural Resource Economics, edited by J. Wesseler, H.P. Weikard, and R.D. Weaver, pp. 93–112. Edward Elgar Publishing, Cheltenham, UK; Northampton, MA, USA.

Miller, K.A. 2007. Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. *Mar. Policy* 31: 56–70.

Miller, K.A. and Munro, G.R. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. *Mar. Resour. Econ.* 19: 367–393.

Munro, G.R. 1990. The optimal management of transboundary fisheries: game theoretic considerations. *Natural Resource Modeling* 4(4): 403–426.

Munro, G.R. 2008. Game theory and the development of resource management policy: The case of international fisheries. In *Game Theory and Policymaking in Natural Resources and the Environment*, edited by A. Dinar, J. Albiac, and J. Sánchez-Soriano, Routledge Explorations in Environmental Economics, chap. 2, pp. 12–41. Routledge, London, UK; New York, USA.

Nordhaus, W.D. and Yang, Z. 1996. A regional general equilibrium model of alternative climate change strategies. *American Economic Review* 86(4): 741–765.

Ricker, W.E. 1954. Stock and recruitment. *Journal of the Fisheries Research Board of Canada* 11: 559–623.

Sandal, L.K. and Steinshamn, S.I. 2002. Optimal age-structured harvest in a dynamic model with heterogeneous capital. SNF Working Paper 84/02. Samfunns- og Næringslivsforskning AS [SNF, Institute for Research in Economics and Business Administration], Bergen, Norway.

- Steinshamn, S.I. 1993. Torsk som nasjonalformue. En disaggregert model. SNF Working Paper 61/93. Samfunns- og Næringslivsforskning AS [SNF, Institute for Research in Economics and Business Administration], Bergen, Norway.
- Steinshamn, S.I. 1994. Bærekraftigutvikling i fiskerinæringen: Kyst fiske vs. havfiske etter torsk. SNF Working Paper 85/94. Samfunns- og Næringslivsforskning AS [SNF, Institute for Research in Economics and Business Administration], Bergen, Norway.
- Stenevik, E.K. and Sundby, S. 2007. Impacts of climate change on commercial fish stocks in Norwegian waters. *Marine Policy* 31: 19–31.
- Sumaila, U.R. 1997. Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock. *Environmental and Resource Economics* 10: 147–165.
- Sumaila, U.R. 2002. Marine protected area performance in a model of the fishery. *Natural Resource Modeling* 15(4): 439–451.
- Sundby, S. 2000. Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. *Sarsia* 85(4): 277–298.
- Vikebø, F., Sundby, S., Ådlandsvik, B., and Fiksen, Ø. 2005. The combined effect of transport and temperature on distribution and growth of larvae and pelagic juveniles of Arcto-Norwegian cod. *ICES Journal of Marine Science* 62(7): 1375–1386.
- Yang, Z. 2003. Reevaluation and renegotiation of climate change coalitions—a sequential closed-loop game approach. *Journal of Economic Dynamics and Control* 27: 1563–1594.

Appendix

Biological model

The catch of fish (Y) in fishery i in fishing season k in year t is given by

$$Y_{k,t}^i = \sum_a \frac{q_a f_{k,t}^i}{q_a \sum_{i=1}^I f_{k,t}^i + M} \times N_{a,k,t} w_a \left\{ 1 - \exp \left[\left(-q_a \sum_{i=1}^I f_{k,t}^i - M \right) \Delta_k \right] \right\}. \quad (\text{A-1})$$

where q is a parameter expressing the vulnerability of each age group of fish to fishing, *i.e.*, the catchability coefficient, f is the fishing effort, M is natural mortality, $N_{a,k,t}$ is the number of fish of age a at the beginning of season k , w_a is the weight of fish at age a , and Δ_k is the length of season k . There are two fishing seasons, the spawning season, which covers the first third of the year^{A-1}, and the rest of the year, so that Δ , the length of the fishing season, is one third and two-thirds, respectively. After each fishing season, the stock redistributes itself and spreads over a smaller area if the stock size is less than in the previous season. Thus, if the fishing effort is given, the fishing mortality becomes

$$F_{a,k} = q_a \times f_k \quad (\text{A-2})$$

The number of fish present in each age group at the beginning of each fishing season is determined by the number of three year old fish and the mortality these fish have suffered since then. A time series of 3-year-old Northeast Arctic cod recruits in the Barents Sea is taken from ICES (2008). The number of three year old fish in the model is determined by the size of the spawning stock through a recruitment function.

Figure A-1 shows a plot of recruits in year t (1949-2007) against the spawning stock

^{A-1}The spawning stock biomass (SSB) is the mature part of the stock that have suffered neither fishing nor natural mortality half-way through the spawning season.

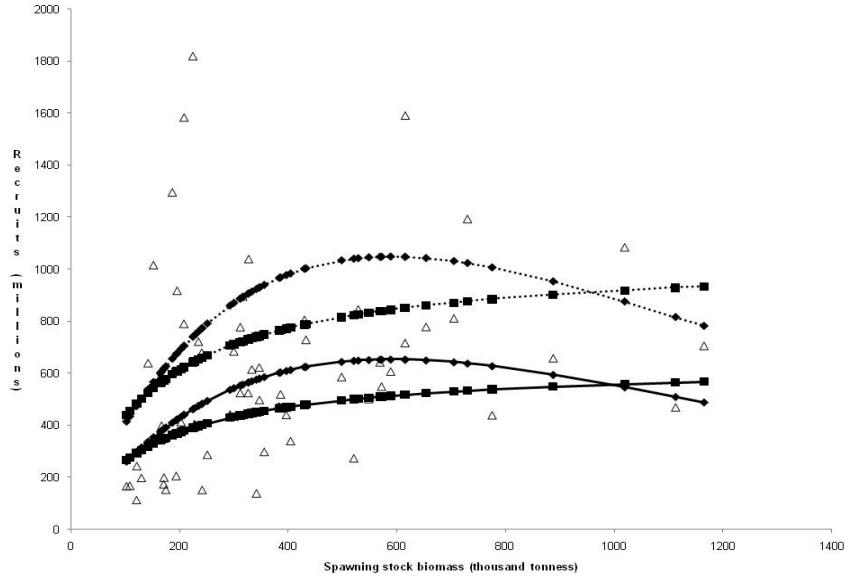


Figure A-1: Observed stock-recruitment 1946-2007 (\triangle), Beverton-Holt (\blacksquare) and Ricker (\blacklozenge), recruitment functions fitted to data on spawning stock biomass, recruitment at age 3 and temperature (the Kola Section); 1946-2007 for temperatures 4°C (solid) and 5°C (dotted), respectively.

biomass in year $t - 3$ (1946-2004). As can be seen, there is enormous variability in recruitment, but it appears that large year classes are less likely to occur if the spawning stock biomass exceeds a certain size. Furthermore, Figure A-1 shows the Ricker (1954) (Equation A-3) and Beverton and Holt (1957) (Equation A-4) recruitment relationship based on both the spawning stock biomass (SSB_{t-3}) and the sea temperature at spawning (τ_{t-3}), at temperatures of 4°C (the average of the Kola Section) and 5°C . In contrast to the Beverton-Holt function, the Ricker recruitment function is able to capture the fact that the recruitment may decline when the spawning stock biomass grow beyond a certain limit.

$$R_t = N_{3,1,t} = SSB_{t-3} \exp(\alpha_R + \beta_R SSB_{t-3}) \times \exp(\gamma_R \tau_{t-3}). \quad (\text{A-3})$$

$$R_t = N_{3,1,t} = \frac{\exp(\alpha_{BH}) SSB_{t-3}}{1 + \exp(\beta_{BH}) SSB_{t-3}} \times \exp(\gamma_{BH} \tau_{t-3}). \quad (\text{A-4})$$

Table A-1: Stock-recruitment and temperature relationships. Estimation results

Ricker stock-recruitment	
$\alpha_R = -0.786$	[$SE = 0.664$]
$\beta_R = -0.0017$	[$SE = 0.00032$]
$\gamma_R = 0.472$	[$SE = 0.174$]
$R^2_{adjusted}$	= 0.32
Beverton-Holt stock-recruitment	
$\alpha_{BH} = -0.497$	[$SE = 0.655$]
$\beta_{BH} = -4.951$	[$SE = 0.688$]
$\gamma_{BH} = 0.543$	[$SE = 0.184$]
$R^2_{adjusted}$	= 0.31

Table A-2: Maturity, weight (kg), and catchability at age

Age	Maturity	Weight	Catchability
3	0	0.341	0.06
4	0	0.692	0.16
5	0.032	1.253	0.39
6	0.121	2.041	0.63
7	0.272	3.079	0.85
8	0.451	4.418	0.99
9	0.626	6.017	1.04
10	0.790	7.990	1.05
11	1	9.431	1.01
12	1	10.217	1.13
13+	1	12.563	1.14

Estimating the coefficients of the Beverton-Holt recruitment curve (Table A-1) essentially produced a horizontal line which falls to zero as it approaches the y -axis. With the observed recruitment being the way it is this is not surprising. Assuming a recruitment that is independent of the spawning stock must be deemed unrealistic. Hence we do not consider the Beverton-Holt recruitment function any further.

For maturity-at-age parameters, ages 5-10, and weight-at-age (w_a) in stock and catches, ages 3-13+, we use the historical mean values presented in Kovalev and Bogstad (2005) (Table A-2). Furthermore, following Kovalev and Bogstad (2005), for ages 3-4

we assume that none of the individuals are mature and that for ages 11+ all are fully mature.

The age-specific catchability coefficients (q_a) used comes from regressing the time series of age-specific fishing mortalities from ICES (2008), that reports the results of a catch-at-age analysis (VPA, Virtual population Analysis) on all reported catches, on the age-specific biomass, resulting in estimates on catchability-at-age and fishing effort (Ekerhovd in preparation) (Table A-2).

Sustainable yield

Using the catch and fishing mortality relationship along with the Ricker recruitment function gives the yield as a function of fishing mortality (F), spawning stock biomass and total biomass, as shown in Figure A-2. Furthermore, the yield is shown (dashed line) as it is after a 500 year long simulation over a number of different fishing mortalities (F). In addition, the solid line shows then yield averaged over the last 250 years of the simulation. For F larger than 0.2, the lines are both smooth and identical . However, below this level of F the single year yield path is not smooth with considerable change in yield as F increases or decreases. With low levels of F the spawning stock biomass will increase, and the recruitment with it, but only up to a certain point. If the spawning biomass increases beyond this point the recruitment will fall and eventually the (spawning) biomass will start to decline. When the spawning biomass again enters the interval where there is a positive relationship between the spawning stock size and the number of recruits entering the fishery three years after spawning the decline in biomass will stop, and the entire process will repeat itself. This explains the fluctuations in the yield at lower levels of F . On the other hand, the average yield as a function of F is nearly symmetric, implying a sustainable yield of about 730 thousand tonnes obtained at $F = 0.43$, while the actual fishing mortality during the last thirty years has been well in excess of that. Recent estimates by fishery biologists show fishing mortalities ranging from 0.27 to 1.3, with an

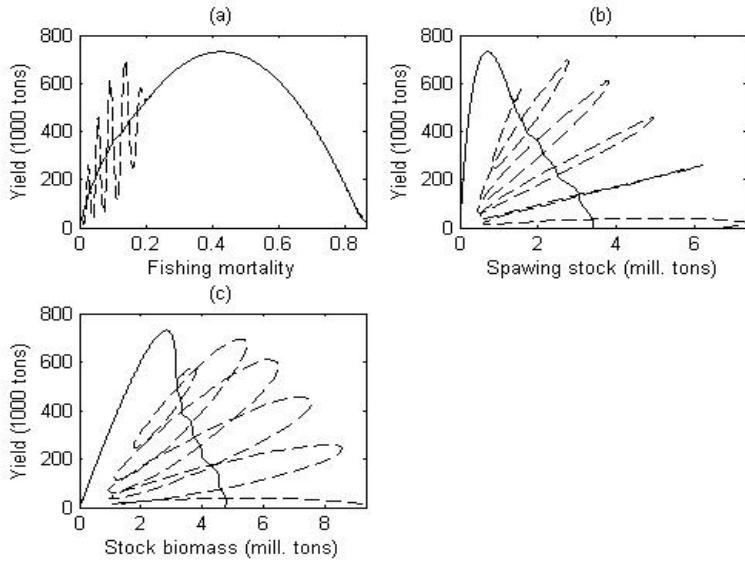


Figure A-2: Sustainable yield, assuming a Ricker stock-recruitment relationship, as a function of (a) fishing effort (f), (b) spawning stock biomass, and (c) total stock biomass. The dashed line shows the yield at the end of a 500 years simulation period, and the solid line shows the average yield over the last half of the simulation period .

average of 0.74, for the NEA cod in the period 1977-2007 (ICES 2008). According to Figure A-2 it would take a fishing mortality of 0.86 to wipe out the stock, which occurs through not permitting any fish to survive until age of maturity.

The sustainable yield rises quickly as the spawning stock is increased and then falls slowly as the spawning stock increases further. The relationship between sustainable yield and the total biomass of the stock is different. Sustainable yield rises almost linearly with the total stock biomass and then falls sharply before the rate of decline slows down again. The reason for this is that a large spawning stock is detrimental for recruitment, according to the Ricker curve. The pristine biomass would thus not correspond to the carrying capacity of the environment; by reducing the spawning stock somewhat it would be possible to improve recruitment as to increase the steady state biomass. It is possible to reconcile this with biological realities by invoking competition for food at the egg and larval stage; if too many eggs and larvae compete, most might get too little to survive, whereas less competition would allow more to survive. Cannibalism from older fish would

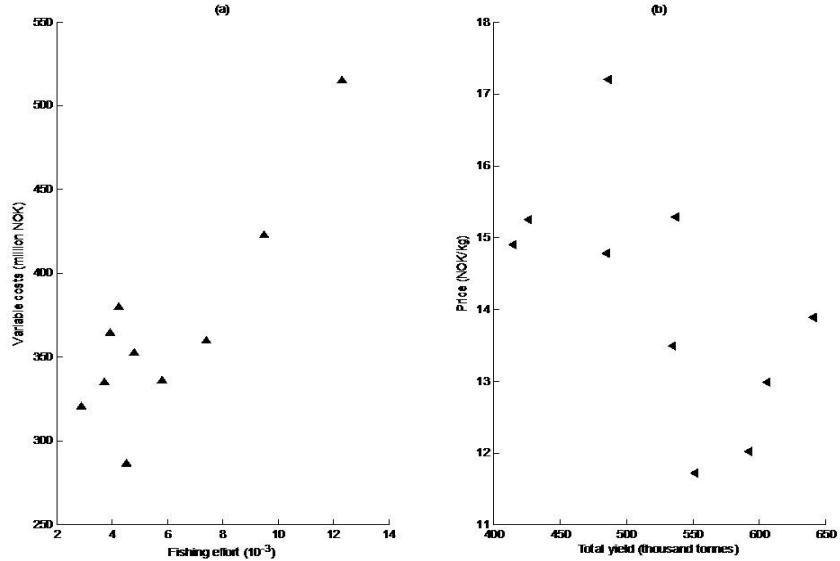


Figure A-3: (a) Total Norwegian variable costs and efforts \blacktriangle and (b) the Norwegian cod prices and total yield \blacktriangleleft in the Northeast Arctic cod fishery, 1998–2007. The operation costs includes both fixed and variable costs, excluding wages and remuneration of the crew. All costs and prices are in real 2007 NOK

cause the same effect, if the total stock is large there might be shortage of suitable prey or the living areas of juvenile and adult individuals would overlap and the young ones would be eaten by the older ones.

Economic model

The profits of fleet i in season k in a given year t are determined by:

$$\Pi_{k,t}^i = \text{Price}(Y_t^I) \times Y_{k,t}^i(X_{k,t}, f_{k,t}^i) - \text{Costs}^i(f_{k,t}^i), \quad (\text{A-5})$$

where $X_{k,t}$ is the state of the stock at the beginning of season k in year t .

Figure A-3 (a) shows the Norwegian variable operation costs in the NEA cod fishery (Fiskeridirektoratet 1998–2007)^{A-2}, plotted against the corresponding fishing efforts^{A-3}.

^{A-2}The crew on fishing vessels are paid a share of the gross catch value, so wages, and in particular the remuneration, are correlated with the catch size. Therefore, wages and crew remuneration, and some unspecified costs known to include the write-off costs of fishing licenses, are not included in the costs estimations.

^{A-3}The fishing effort estimates is based on a time series of fishing mortalities from ICES (2008) that

There is an indication of a positive linear relationship between the operating costs and fishing effort. We can test this by fitting Equation A-6 to the data. Hence,

$$Cost_t^i = \gamma + \kappa \times f_t^i, \quad (\text{A-6})$$

where γ is the fixed costs, and κ a variable costs parameter.^{A-4} The estimation results from fitting the cost function to the data are presented in Table A-3. The model explained 71% of the variation in the cost-effort data.

Figure A-3 (b) shows the Norwegian prices plotted against total yield in the NEA cod fishery, 1998–2007^{A-5}. By using the total yield instead for the Norwegian catches only, we assume that all the NEA cod catches are sold in the same market. There seems to be a negative relationship between the prices obtained and the quantity caught, i.e., the prices decline if the total yield increases. Since Figure A-3 (b) indicates a direct linear relationship between prices and total yield we will estimate a linear price function.

$$Price_t = p - \omega \times Y_t^I, \quad (\text{A-7})$$

where p is the price of fish when total landings approaches zero, ω is the factor for how much the price declines as the total landings increases. The results of this estimation are also presented in Table A-3. The model was able to explain 26% of the variation in the price-yield data.

reports the results of a catch-at-age analysis (VPA, Virtual population Analysis) on all reported catches (Ekerhovd in preparation). The Norwegian shares of the total effort in the fishery are proportional to Norway's shares of the total landings (Fiskeridirektoratet 1998-2007).

^{A-4}It is only the pure variable costs that are relevant for the strategic choices made. The players would choose a positive effort level as long as the contribution margin is positive

^{A-5}The information on the Norwegian prices comes from the Norwegian Directorate of Fisheries annual profitability survey on the Norwegian fishing fleet – whole year operating vessels 8 meters over all length and above (Fiskeridirektoratet 1998-2007).

Table A-3: Norwegian variable harvest costs and effort, and prices and total yield, 1998-2007: Estimation results

Cost-effort relationship		
Constant:	$\gamma = 258.89[SE = 25.05]$	million NOK
Variable costs:	$\kappa = 18327.32[SE = 3823.4]$	million NOK
	$R^2_{adjusted} = 0.71$	
Price-yield relationship		
Maximum price:	$p = 21.036[SE = 3.40]$	$NOK \times kg^{-1}$
Yield factor:	$\omega = 0.013[SE = 0.006]$	$NOK \times kg^{-1}$
	$R^2_{adjusted} = 0.26$	