Non-Cooperative Exploitation of Multi-Cohort Fisheries - The Role of Gear Selectivity in the North-East Arctic Cod Fishery

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Abstract

North-East Arctic cod is shared by Russia and Norway. Taking its multi-cohort structure into account, how would optimal management look like? How would non-cooperative exploitation limit the obtainable profits? To which extent could the strategic situation explain today's over-harvesting? Simulation of a detailed bio-economic model reveals that the mesh size should be significantly increased, resulting not only in a doubling of economic gains, but also in a biologically healthier age-structure of the stock. The Nash Equilibrium is close to the current regime. Even when effort is fixed to its optimal level, the non-cooperative choice of gear selectivity leads to a large dissipation of rents.

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Key words: Differential game, Gear selectivity, Multi-cohort fisheries, North-East Arctic cod, Optimal harvest policies

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1. Introduction

The Barents Sea is a rich and productive ecosystem. North-East Arctic cod *(Gadus morhua)* is by far the most valuable biological resource of this ocean. The fish stock, which is shared by Russia and Norway, is one of the world's largest populations of Atlantic cod. It is considered to be within safe biological limits (ICES, 2008) and the Joint Russian-Norwegian Fisheries Commission manages the exploitation of the resource by agreeing on an annual catch quota and on several technical regulations. In spite of this, the resource appears to be over-exploited. Scientific analysis has repeatedly shown that the harvesting pattern is "hugely inefficient"(Arnason et al., 2004, p.531). Not only have catches and quotas been consistently above scientific advice (Aglen et al., 2004), but catch by age has also been shifted towards younger age classes with industrial exploitation (Ottersen, 2008).

Here we identify prospective gains from improved management practice and contrast these to the result of a non-cooperative game. How does an optimal management regime look like and how is it limited by non-cooperative exploitation? To which extent could such a strategic international situation explain today's over-harvesting? In order to answer these questions, three scenarios have been simulated:

1. A continuation of the current harvesting pattern.
2. Optimal management of a hypothetical sole owner who maximizes economic gain.
3. Exploitation from two agents unable to make binding agreements.

The first scenario may be interpreted as the outcome where Russia and Norway face constraints from the political process and the behaviour of fishermen. The second scenario represents the first-best outcome that a social planner would employ and where the rents from fishing are divided by some unspecified transfer mechanism. The third scenario constitutes an intermediate case where both Russia and Norway are able to control perfectly their own exploitation but fail to jointly manage the fish stock in an efficient manner. This could be an appropriate description of the strategic situation as cooperative agreements are not enforceable in international relations and the actual harvesting decision is difficult to observe. [1]

There exists a large literature on the North-East Arctic (NEA) cod fishery (e.g. Hannesson, 1975; Steinshamn, 1993; Sumaila, 1997b; Armstrong and Sumaila, 2001; Sandal and Steinshamn, 2002; Arnason et al., 2004; Kugarajh et al., 2006). The Russian-Norwegian interactions have been analyzed by Armstrong and Flaaten (1991); Sumaila (1997a); Stokke et al. (1999); Hannesson (1997, 2006, 2007), but mainly in a cooperative setting. In general, game theory has been fruitfully applied to fishery economics (see Kaitala and Lindroos (2007) for an overview). Although the multi-cohort structure of the stock is taken into account by many analyses, there is, to the best of our knowledge, not any application of a non-cooperative differential game to an age-structured resource. For a general survey of age-structured optimization models in fisheries bioeconomics, see Tahvonen (forthcoming).

This is especially relevant as our work shows that the choice of gear selectivity is of paramount importance for the outcome. In fact, that the minimum size of fish could be a control dimension of great consequence has generally been overlooked so far, in spite of the early result from Turvey (1964, p.74), who writes) "...that either mesh regulation or the control of fishing effort is better than nothing but that regulation of both is still better."

Another important feature of this study is that it rests upon an ecological model which has been derived through statistical analysis of time-series data from the Barents Sea system (published in Hjermann et al., 2007). The economic model is essentially a simplified version of the one employed in Diekert et al. (2009). In order to highlight the effects of non-cooperative exploitation, we have concentrated on one gear type (trawl) and have made the players Russia and Norway symmetric. Because the state of the fish

[1] For example, illegal, unreported, and unregulated (IUU) fishing on a huge scale is a major problem in the area (Hjermann et al., 2007; Hannesson, 2007).

stock and the agent's exploitation decisions are only imperfectly observable, we postulate an open-loop information pattern and aim for Nash Equilibria of this kind. A procedure that finds stable equilibria by iteratively updating best responses has been designed.

By this interdisciplinary approach, we are able to point out that the gains from optimal management could be substantial. In particular the choice of a larger mesh size than currently employed is taking the individual growth potential of the fish into account. However, the agents fail to do precisely this in a non-cooperative game. Rather, the nets are tightened to catch the fish before the respective opponent does. The outcome of the non-cooperative game is indeed close to the simulation of the current harvesting pattern. The article proceeds as follows: Section 2 develops the bio-economic model, section 3 discusses the simulation approach, results are presented in section 4, and section 5 concludes.

2. Model

2.1. *Biological Model*

The biological model describes the number of cod ($N_{a,t}$) of a given cohort of age a at time t, its average length-at-age l_a, weight-at-age w_a, and its average maturity probability mat_a. Somatic growth and maturation are assumed to depend only on age. The values result from regressions on ICES data, and are given as time-independent parameters (Table 1). Cod keeps on growing with age also after maturation, and they may reach an age of 24 years and a weight of 40 kg (Aglen et al., 2004). Due to natural mortality and the high fishing intensity in recent times, however, few fish survive an age of 12 years (ICES, 2008). In fact, the main part of the catch today is between 4 and 5 years old and weighs 1-2 kg. Nevertheless, it is important to include more age-classes in the bio-economic model, as the results of the simulations could otherwise seriously underestimate the growth potential of the resource (Hannesson, 1993). Age a therefore runs from 3 to 15.[2] The total biomass of the stock is the sum of the biomass of each age group ($x_{a,t} = N_{a,t} w_a$: number of fish multiplied with their average individual weight).

[Table 1 here]

The function for the recruitment of fresh cod to the fishery assumes that the cod's spawning stock biomass[3] (SSB) and recruits are linked by the Beverton-Holt relationship (Beverton and Holt, 1957). The effect of temperature was added as it significantly improved the fit of the model.[4] The number of recruits $N_{3,t}$ is given by (1) and from then on the number of cod develops according to the difference equation (2):

$$N_{3,t} = \frac{\exp(\alpha) \cdot SSB_{t-3}}{1 + \exp(\beta) \cdot SSB_{t-3}} \cdot \exp(\gamma \cdot temp) \tag{1}$$

$$N_{a+1,t+1} = N_{a,t} \cdot (1 - F_{a,t}) \cdot e^{-M} \tag{2}$$

The estimated coefficients are $\alpha = -0,4684$ [SE $= 0,65$], $\beta = -4,8522$ [SE $= 0,69$], $\gamma = 0,5517$ [SE $= 0,18$], where SE stands for standard error. M is the instantaneous natural mortality, conventionally set to 0,2 for all cohorts (ICES, 2008), and $F_{a,t}$ is the effective age-specific fishing mortality (explained below). Fishing and natural mortality occur sequentially; first the proportion of a cohort which is fished is removed, and those that subsequently survive natural mortality make up the next age-group at the beginning of the next year. The "effective fishing mortality" (the probability that a fish of given age is caught at a given time) constitutes the link to the economic model.[5]

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[2] Three years is presumed to be the age of recruitment into the fishery. That is, 3 year old fish have grown sufficiently large to be susceptible for being caught. A cohort reaches its maximum biomass with 12 years and not many individuals would become older than 15 years even in absence of fishing pressure.
[3] The spawning stock biomass is defined as the sexually mature part of the stock: $SSB_t = \sum_{a=3}^{15} x_{a,t} mat_a$.
[4] Temperature has, at least during the last decades, turned out to be closely correlated with the recruitment success of cod, i.e. cod abundance at age 3 (Ottersen et al., 2006). More precisely, it is a good proxy for the general environmental conditions that determine the survival probability of the larvae during its first five months. The mean temperature of the period 1949-2007 was 3.9921°C (standard deviation 0,46).
[5] The term "effective fishing mortality" is introduced in order to call attention to the difference to traditional Beverton-Holt modeling, where fishing mortality is instantaneous and would enter the accounting equation exponentially.

2.2. *Economic Model*

The alternative management scenarios are characterized by the economic decisions of the agents. As future changes both in the underlying biological and economic parameters are hardly predictable (Shepherd and Pope, 2002), we concentrate on a simulation of average conditions. Consequently, we abstract from changes in prices or technology over time and from capacity decisions/constraints. Agents maximize the sum of discounted annual profits over the whole time horizon by choosing effort and gear selectivity. A discount rate of 5% (implying $\delta = 0,9523$) is chosen. Although rather high, this is advantageous for the simulation because it makes the distant periods less important for the Net-Present-Value (NPV).[6]

For simplicity, it is assumed that the Russian (R) and Norwegian (N) fishing fleet are symmetrical. The instantenous profits of fleet $i = R, N$ in a given year t are determined by:

$$\pi_t^i(x, E, m) = \sum_{a=3}^{15} p_a \cdot H_{a,t}(x, E^i, m^i) - c(E^i) \tag{3}$$

Where p_a is the age-specific price, $H_{a,t}(x, E^i, m^i)$ is the age-specific harvest function, and $c(E^i)$ is the cost function. We will describe each of these in turn.

In order to focus on the strategic interaction, we have assumed perfectly competitive market prices p_a for the different age classes[7] (Table 2).

[Table 2 here]

The harvest function tells how many fish of age a are caught at time t by fleet i.

[6] The Norwegian Ministry of Finance for example is employing a discount rate of 4% and in larger Europe public investment are discounted at a similar rate. (`http://www.regjeringen.no/Upload/FIN/Vedlegg/okstyring/rundskriv/faste/r_109_2005.pdf`)

[7] This might be not too unrealistic: 90% of the cod products are exported, and the price which the Norwegian fishermen receive is largely determined by the negotiations between the organization for the fishing industry and the fishermen's sales organization (Sandberg et al., 1998). These minimum prices have been employed after it has been accounted for the fact that these prices are given for headed and gutted fish while the fish in the model and in the ocean are whole. Norges Råfiskelag, Pressemelding (May 3, 2007) `www.rafisklaget.no/pls/portal/url/ITEM/6D4F5250DAD24D22A026C2F97847477B`

$$H^i_{a,t} = x_{a,t} \cdot \underbrace{r(m) \cdot (1 - e^{-q \cdot E})}_{F^i_{a,t}} \tag{4}$$

It depends on the amount of available biomass $x_{a,t}$ and on the effective fishing mortality $F^i_{a,t}$ applied to the respective age-class/cohort. The age-specific fishing mortality in turn depends on the gear specific selectivity $r(m)$, which defines "the probability that a fish of length $[l_a]$ is captured, given that it contacted the gear [with mesh size m]"(Millar and Fryer, 1999, p.92). The condition that a fish has contact with the gear then depends on the amount of effort applied which is scaled by the fleet specific catchability q. The term qE does therefore not denote the fishing mortality as such, but rather the intensity at which fish are exposed to the gear. In the limit, as $E \to \infty$, all fish have contact with the gear. In other words, effort controls how many fish are potentially exposed to fishing mortality, while the mesh size, as a separate control variable, determines which fish actually die due to fishing.

Trawlers catch the fish by actively pulling a net through the water with a speed higher than the targets' maximum speed. The fish is thereby overtaken and must pass through the netting to escape. The size of its mesh openings determine the gear selectivity (Millar and Fryer, 1999). Accordingly, few fish below and most fish above a certain size are caught (the gear selectivity curve is S-shaped). Building on literature in fisheries research (Kvamme, 2005; Halliday et al., 1999), the following specific selectivity curve for trawl nets is used:

$$r(m) = \left(1 + \exp\left(\frac{-2,2}{\{0{,}112m - 4{,}335\}} \cdot (l_a - \{0{,}499m - 16.105\})\right)\right)^{-1} \tag{5}$$

In general, a larger mesh-size moves the selectivity curve to the right, but it also makes the selection range larger, so that the curve gets flatter. It is plotted for various mesh sizes below (Figure 1).

[Figure 1 here]

The catchability coefficient q is influenced by the composition of the fishing fleet, the effort and skill of the fishermen, as well as the distribution and behaviour of the fish

(Kvamme, 2005). Given the information about the gear selectivity and the effort applied from the Norwegian Directorate of Fisheries (Fiskeridirektoratet, 1998-2002) as well as the fish stock for the period 1998-2002 from ICES (2008), equation (4) is used to calibrate the coefficient[8] as $q = 2,67 \cdot 10^{-8}$.

A model which portrays the strategic situation in the NEA cod fishery should take the spatial distribution of the stock into account, since the two nations have sovereignty only in their territory. However, they concede each other the right to fish large parts of their quota in their respective zones. For simplicity, it is therefore assumed that both trawler fleets have complete access to the entire biomass. Nevertheless, a fish must not be caught twice in the model. To this end, the effort of both trawlers enters as sum in the exponent of (6a,b) and the last term assigns the respective share according to the fleet's effort:

$$F^N_{a,t}(E,m) = r(m^N) \cdot (1 - e^{-q \cdot (E^N + E^R)}) \cdot \frac{E^N}{E^N + E^R} \tag{6a}$$

$$F^R_{a,t}(E,m) = r(m^R) \cdot (1 - e^{-q \cdot (E^R + E^N)}) \cdot \frac{E^R}{E^N + E^R} \tag{6b}$$

The cost of choosing a certain gear, or to this end, a certain minimum mesh size, are only incurred when the vessel is rigged. Also, the expenses are probably not dramatically different whether one buys/produces a net of one mesh size or the other. As we concentrate on short-term costs, the cost function is assumed to depend only on the effort applied. Effort is defined as tonnage-days. The cost data was obtained from the profitability surveys of the Norwegian Directorate of Fisheries (Fiskeridirektoratet, 1998-2002). The following functional form and parameters (in NOK) gave the best fit among a series of convex cost functions:

$$c(E) = c_1 E^2 + c_2 \qquad c_1 = 8,6 \cdot 10^{-6}, c_2 = 10,4 \cdot 10^8 \tag{7}$$

[8] The same value of q is assumed for both trawling fleets, because there is no reason to presume that the skill of Russian fishermen differs in any systematic way from that of their Norwegian counterparts.

3. Simulation

Optimal harvesting of a multi-cohort stock – be it in a sole-owner or in a competitive setting – really implies two questions for the agent: Fish of which age should be targeted, and how many fish should be removed? The individual fish gain weight with age, but at a decreasing rate. At the same time, the number of fish in a given cohort declines due to natural mortality. Consequently, the biomass of a given cohort will first increase and then decrease with age. If one waits too long, too many fish will have succumbed to natural mortality, while contrarily it should be avoided to fish inefficiently small specimen ("growth overfishing"). Moreover, as the fish mature quite late (age 6-7), one also needs to avoid taking all fish before they were able to spawn ("reproductive overfishing").

However, the optimal amount of harvested fish is not controlled directly. Rather, it is effort E and mesh size m which are chosen over time. There will be three modes of the cooperative and non-cooperative simulations: one where both E and m are controls (named *...–Em*), one where only mesh size can be controlled (*...–m*), and one where only effort is the choice variable (*...–E*). Separating the two control dimensions in this way allows to study the particular effect on the harvesting pattern.

The results from optimal harvesting (*SoleOwner-...*) will then be contrasted to (i) a game of two agents which fully control their own harvesting, but are unable to make binding agreements (*Game-Em*). Additionally, non-cooperative exploitation will be simulated (ii) when effort is fixed to the optimal path and only m is chosen (*Game-m*), and (iii) when the mesh is fixed to the optimal size and only E is chosen (*Game-E*). Finally, in order to simulate the continuation of today's harvesting regime, *StatusQuo* refers to an application of the current [9] E- and m-levels over the whole time period. An overview of the different simulation scenarios is given in Table 3

[Table 3 here]

The problem of the *SoleOwner* will then be:

[9] That is, more precisely, the average of the values of 1998-2002: 11 million units (= *tonnage-days*) of effort and a mesh size of 135 mm.

$$\max_{u_t} \sum_{t=0}^{T} \delta^t \cdot [\pi^R(x_t, u_t^R, u_t^N) + \pi^N(x_t, u_t^R, u_t^N)]$$
$$\text{subject to : the biological system } x_t \text{ and controls } u_t \in U \tag{8}$$

- The *SoleOwner* controls both fleets. As it can be seen from (3), (7), and (6), the objective function is concave and the control region $U = (E, m)$ is convex since $E \in [0, \infty)$ and $m \in [60, 300]$.
- The model is solved for $T = 75$ years. The long time horizon ensures that the reported solutions for the first 50 years will be numerically indistinguishable from the infinite horizon case.[10]
- The biological system, summarized by x_t, is specified by the vector of biomass with the recruitment function (1) giving the entry $N_{3,t}$, and the entries for $a = 4, ...15$ according to the cohort development (2) as well as the weight, length, and maturity parameters summarized in Table 1. As a short-hand notation the system is written as $x_{t+1} = f(x_t, u_t^R, u_t^N)$ for $t = t-3, t-2, t-1, t$. The initial state x_0 is given by the latest number assessment of ICES (2008).

As the actions of the agents influence the development of the resource (payoff-relevant strategies), a repeated game approach is not suitable (Yang, 2003). Instead a *discrete time differential game* (Başar and Olsder, 1995) will be applied, which is described by:

- the number of players: Russia and Norway $i = R, N$.
- the number of stages $t = \{0, 1, ..., T\}$.
- the control variable u^i of player i which belongs to the set of admissible controls U^i as in problem (8).
- the state $x_{t+1} = f(x_t, u_t^R, u_t^N)$ describing the biological system as above.
- finally, the pay-off functions of the players which are for Russia and Norway respectively:

[10] See Nævdal (2003) for an elaboration of this approach.

$$J^R = \sum_{t=0}^{T} \delta^t \cdot \pi^R(x_t, u_t^R, u_t^N)$$
$$J^N = \sum_{t=0}^{T} \delta^t \cdot \pi^N(x_t, u_t^R, u_t^N)$$

Each agent will choose a strategy which maximizes his NPV. The choice of player i will therefore be a *best reply* 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 u^{i*} thus satisfy:

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

In their pioneering work, Levhari and Mirman (1980) find each period's equilibrium backwardly by equating the player's reaction functions. It is a Cournot-Nash solution and the sequence of decisions is itself a stable equilibrium.

The notion of stability is of particular importance in fishery games. The state is – if at all – only vaguely known as the biological system is inherently uncertain and volatile. If a deterministic model is used nonetheless, it should be provided that small errors do not lead to an entirely different outcomes. Consider the following sequence of moves: Given an equilibrium solution, player 1 deviates from his strategy (or player 2 makes a mistake in his observation of the situation). Player 2 now re-adjusts his strategy to the best of his knowledge. Player 1 reacts to the new strategy of player 2, upon which player 2 again optimally reacts to the optimal reaction, etc. Therefore (Başar and Olsder, 1995, p.178):

A Nash-Equilibrium u^{i*} is said to be stable if it can be obtained as the limit of the iteration:

$$u^{i*} = \lim_{k \to \infty} u^{i(k)}$$
$$u^{i(k+1)} = \arg\max_{u^i \in U} J^i(x, u^i, u^{j(k)})$$

The problem has been solved numerically for the *SoleOwner* optimization and the *Game*. Yet the software, Premium Solver by Frontline systems, cannot handle algebraic variables and it is consequently not feasible to equate reaction functions as in Levhari and Mirman (1980). This problem is circumvented by designing a procedure which exploits the desired property of stability. What the Solver can do, is to solve one problem from the perspective of one player at a time. For example, the tool finds the path of Russian effort which is optimal given the development of the state and specific Norwegian control values. The algorithm then switches perspective and Solver optimizes the exploitation pattern of the other player, etc. Similar to the adjustment process in the standard Cournot game (Fudenberg and Tirole, 1991, p.23), the process of iteratively updating best replies lets the player's strategies converge to the open-loop equilibrium paths. The procedure has been applied from a set of ten random starting values which all yielded the same result (but for deviations in the order of one per mille, which are attributable to numerical imprecision).

In order to validate that the players do not regret the plans of actions they have decided upon, we follow the approach of Yang (2003) by constructing a sequence of open-loop equilibria over the time horizon $t = s$ to $T + s$ for $s = \{0, 1, \ldots, T\}$. As the outcome is identical to the original solution, the solution is *time-consistent* in the sense that it constitutes a Nash Equilibrium for every subgame along the equilibrium path (Dockner et al., 2000, p.99). It is however not necessarily *subgame-perfect* as it might not be a Nash Equilibrium for every conceivable subgame (Dockner et al., 2000, p.102).

4. Results and Discussion

An overview of the results is given by Table 5 (all results except the standing stock biomass are the steady state values for one of the two symmetric fleets). Figure 2 displays the development of biomass and harvest over time for the status quo, the optimal cooperative scenario, and the non-cooperative game. Furthermore, Figure 3 shows the effort and mesh size paths for all simulation scenarios. The results from a sensitivity analysis, showing that the simulation outcomes are robust to reasonable changes in the parameter values are presented in section 4.4.

[Figures 2 and 3]

4.1. *Optimal Management*

Optimal Management would lead to considerable gains. The Net Present Value (NPV) of the entire fishery could be more than doubled compared to the status quo (116 vs. 55 billion NOK). The harvest in steady state would sum up to 647 thousand tons (compared to 392 thousand tons in the business-as-usual simulation). Additionally, the fish stock would develop to a much more robust and abundant level than today (without this being an explicit objective). Not only would the overall biomass (7,5 million tons) be significantly larger, but also the age-structure would be closer to pristine conditions (see Figure 2). This is particularly important as older and heavier individuals are better able to buffer adverse environmental fluctuations, which are presumably amplified by climate change (Ottersen et al., 2006). Assuming that harvesting has not resulted in evolutionary change (Guttormsen et al., 2008), age-specific fisheries management would thus have the potential to reverse the trend to juvenescence and increased variability in the fish stocks (Stenseth and Rouyer, 2008).

The gains of optimal management are achieved by slightly reducing effort (from 11 million units to 9,7 million units), but above all by adjusting gear selectivity so that the right age-class is targeted (see Figure 3). The age where a cohort of cod has reached its maximum value will depend on the specific growth function, the assumed natural mortality M, the market price of fish and on the harvesting cost.[11] In the present model it turns out that this age is around 9 years, where the fish weigh 5-6 kg, while today's catch is mostly 4-5 years old and weighs 1-2 kg on average. Hence optimal management will imply a full appreciation of the resource's age-specific growth potential. This shows very clearly in the composition of the harvest. With mesh-size being a choice variable the gear is tailored (mesh size of $\sim$205 mm) to target this age group and fish of age 9

[11] Note that a price which increases with age effectively makes the individual growth in biomass-value steeper.

and older make up more than 80% of the catch (Figure 4). In contrast, the composition of the *Status Quo* and *Game* harvest consists mainly of inefficiently small fish. (Fish of age 9 and older sum up to 21% or less of of total harvest.)

[Figure 4 here]

The importance of targeting the right age-class is further illustrated by the simulations where only E or m is a choice variable and the respectively other control is fixed to its current level. When the mesh size is the choice variable, the exploitation pattern remains very similar. The development of biomass and harvest looks almost identical. The mesh size is enlarged to 209 mm to compensate for the somewhat higher effort, but the NPV is with 110 billion NOK close to the *Sole Owner-Em* scenario. Essentially, the simulation shows the effect of a move to the eumetric yield curve (Beverton and Holt, 1957). This result could prove to be very policy relevant, as one could interpret the *SoleOwner-m* simulation as a situation where the management authorities are constrained to the current effort levels (e.g. by political pressure from fishermen) but are able to influence the gear selectivity. In fact, while the phase to build-up the stocks is rather long (it takes 15 years to reach steady state), the fishermen make positive profits already after three years and after six more years fishermen earn double than what they would have earned under status quo.

When the mesh size is fixed to today's level of 135 mm and only effort is chosen, the altogether different exploitation pattern of pulse-fishing emerges to avoid "growth over-fishing" (see Figure 3). Not fishing for some time until the proportion of older individuals in the stock has reached an adequate level and then fishing with high effort is profitable in spite of the convexity of the cost function (though discounting levels the pulses in more distant periods). Not surprisingly, the NPV is lower (91 billion NOK), but still constitutes a significant improvement over the continuation of today's harvesting regime.

4.2. *Non-cooperative Exploitation*

Non-cooperative exploitation severely constrains the management options for the North-East Arctic cod fishery. Whereas under optimal sole-owner management a NPV of 116 billion NOK is achieved with an effort level of 9,7 million units and a mesh size of 206 mm, the Nash-Equilibrium of the game yields a joint NPV of only 67 billion NOK. The average non-cooperative effort level is 10,8 million units and the mesh size is 139 mm.

Essentially, the rivalry implies two negative externalities: First, a fish taken by one agent today, cannot be taken by the other agent today. Second, a fish taken today, cannot be taken tomorrow. Every agent therefore has an incentive to appropriate more of the resource rents to himself, and to catch the fish before his rival does. Acknowledging the age-structure of the fish stock reveals a second dynamic dimension of the problem: A fish may be harvested earlier in time, but also at an earlier age. Harvest is not controlled directly in this model, but determined by the choice of effort (how many fish are caught), and by the choice of mesh size (which fish are caught). The consequence of this incentive structure is then an inefficiently small equilibrium mesh size (∼139 mm). But also the effort level is with 10,8 million units too high. Due to the detrimental effects of non-cooperative exploitation, the steady state harvest per fleet amounts to only 418 thousand tons (see also Fig. 2).

The disaggregated analysis brings out the mechanism of the two negative externalities clearly. Even when the effort level is fixed to its optimal path from the *SoleOwner-Em* scenario, competition in catching the fish at an earlier age leads to a massive dissipation of rents. The mesh size in the Nash-Equilibrium of the *Game-m* scenario is 134 mm. That is, the fish are targeted when they are between 4 and 5 years, implying a loss of 37 billion NOK. In short, the gains from choosing a benign effort path do not materialize if the agents choose the mesh size non-cooperatively . The optimal effort path for this gear selectivity would be pulse fishing (see section 4.1).

When the mesh size is fixed to the optimal level from the *SoleOwner-Em* simulation, the competition in harvesting the fish is played out over the chosen effort. The equilibrium effort then settles at the very high level of 16,8 million units. However, the loss implied by non-cooperation is comparatively smaller (though still significant, see Table 4). The reason is that with a given mesh size of $\sim$205 mm, mainly fish of age 9 and older are targeted. Hence “growth overfishing” is avoided by the very setup. And even though more than the optimal amount of fish is harvested, the stock can develop to a high level. Consequently, the non-cooperative harvest per fleet (651 thousand tons) is quite large in this case. In fact, the joint NPV of this game (190 billion NOK) is higher than the NPV of the *SoleOwner-E* optimization (184 billion NOK) where the mesh openings are fixed to their current size of 135 mm. This further underlines the importance of taking the regulation of the gear specific selectivity into account.

Table 4 illustrates the “prisoner-dilemma”-like structure of non-cooperative exploitation. It shows the resulting payoff NPV (in billion NOK) for the respective dynamic best-replies.

[Table 4 here]

4.3. *A tragedy in the Barents Sea?*

The well-known metaphor of the “Tragedy of the Commons” (Hardin, 1968) predicts the complete dissipation of rents for a shared renewable resource when well-defined property rights cannot be established and access is free. Clark (1980) shows that competition between as few as two agents can lead to the same outcome. However, this need not be the case (Dasgupta and Heal, 1979). Here, the biomass of the cod stock stays well above the safe biological limit of 500 000 t at all times, in spite of non-cooperative exploitation. Neither does the game result in one agent making zero profits, or in the complete dissipation of rents. The reason is that the objective function of the agents is not linear in the controls. Therefore the cost of catching another fish becomes prohibitively expensive for the agents before the stock is harvested down to a level where there are zero profits from fishing.

Nevertheless, the loss implied by non-cooperative exploitation still is dramatic. What might be even more astonishing is the similarity between the equilibrium of the dynamic game and the simulation of the current harvesting pattern. Not only is the harvest composition and the development of the cod stock almost identical (See Figure 2 and 4), but also the players settle for much the same mesh size and effort values as in the status quo case. An application of 11 million units of effort with a mesh size of 135 mm yields a NPV of 55 billion NOK. In the equilibrium of the game, an effort of 10,8 million tonnes is applied with a mesh size of 139 mm yielding a NPV of 67 billion NOK. The surplus is largely due to the more pronounced phase of stock build-up. [12]

If, on the one hand, the outcome of the non-cooperative game lay far above the status quo, the sub-optimality of the current situation would be mainly due to interior management problems. On the other hand, if the current situation would prove to be much better than the non-cooperative result, the assumption of non-cooperative behaviour would have to be rejected. Neither is the case, which suggests the conclusion that the strategic interaction in the Barents Sea can explain the sub-optimality of the current situation to a large extent. [13]

4.4. *Sensitivity Analysis*

As the projections of alternative management scenarios rest on calibrated parameters, the sensitivity of outcomes to changes in the gear selectivity, the discount factor and the cost curve were tested. All in all, the model shows to be robust; reasonable changes in parameters do not lead to radically different results. The main results of the sensitivity analysis are summarized below. [14]

[12] The observation that the biomass is also rising in the first periods of status quo management can be explained by the fact that the average values of trawl effort taken from the data do not include the effort applied by third countries nor, by definition, illegal, unreported, and unregulated fishing.

[13] Obviously the alternative hypothesis that the international behaviour is cooperative and all inefficiency is due to internal non-compliance in spite of the best efforts from the authorities, cannot be rejected by the above argumentation. However, this is not very plausible.

[14] A more detailed account is available as supplementary material online.

Firstly, reducing the selection range (the difference between the length of 25% and the length of 75% retention probability) has the effect of making the selectivity curve steeper (see Figure 1). A steeper selectivity curve allows better selecting for the age-groups that should be targeted. It is therefore no surprise that halving the selection range leads to an increase in harvest, biomass, and NPV for all sole-owner optimizations. In contrast, a sharper selection pattern in the non-cooperative game lead to a more fierce competition to catch younger fish (reducing the mesh size) and consequently a lower income. A less differentiated exploitation pattern (doubling the selection range) obviously had the opposite effect. The comparatively small changes in outcome (around 5%), given a significant change in selection pattern, support the extrapolation of the retention curves to large mesh sizes that are considerably larger than today's.

Secondly, as it was to be expected, changes in the discount rate (to polar cases of 2% and 10% respectively) had the strongest impact on the simulation outcomes. The obtainable NPV was doubled in the 2% scenario and decreased by 60% in the 10% discount scenario. Also, the standing stock (+8% / -14%) and the harvested biomass (+1% / -4%) were larger in the low-discount and smaller in the high-discount scenario, but these changes were much smaller in magnitude. Also the exploitation scenarios remained largely the same (the mesh size was slightly increased in the low discount case and slightly reduced in the high discount case), but for the optimization scenario where only effort was a choice variable: here the high discount rate lead to significantly reduced fishing pulses as it became more costly to wait for the fish to become old.

Thirdly, changing the cost curve by +/- 10% had a negligible effect on the outcome of the simulations. The NPV increased by maximum of 3%, and there was virtually no effect on the exploitation pattern apart from a slightly increased use of effort when it was less expensive to do so, and the opposite when costs were higher. We did not conduct a sensitivity analysis of the Sole-Owner-m simulation for the obvious reason that the mesh size (whose changes were assumed to be costless) was the only control variable.

Finally, the harvest function (equation (4)) implies that a doubling of the stock would also double the harvest for any given amount of effort. This is indeed a highly special case, making the cost of catching one fish inversely proportional to the stock, and hence the size of the stock very important for profits. In order to investigate the importance of this assumption, we have conducted simulations with an alternative set-up, where we have adjusted the price to include a share of the cost of catching one unit of fish [15] and maximized only revenue. [16]

Provided the cost-adjusted price is positive, revenue will be an increasing function of effort (though at a decreasing rate). It would therefore be optimal to make effort as large as possible, were it not for the fact that harvesting all fish today leaves no fish to harvest tomorrow. However, if gear selectivity is a separate control variables, then there are really two levers that can be used to limit harvesting. Therefore one would expect that effort is unrestrained while the effective harvesting is controlled via the mesh size, sparing the fish below the optimal age-at-first-capture and taking all of them above.

In fact, this is the outcome of the alternative simulation scenarios. In the Sole-Owner optimization where both effort and mesh size were choice variables, effort is (but for the first periods of stock rebuilding) at its maximum level (which was arbitrarily set at 110 million tonnage-days for the sake of the numerical procedure) and the mesh size was around 250mm. The overall biomass of the optimal standing stock is the same (in fact, it is slightly increased), but its composition is different: Fish of age 11 and above contribute to a much larger extent. The overall NPV is somewhat reduced. This might seem counterintuitive at first sight since there are no costs of employing effort, but it is due to the significantly reduced prices per kg of fish. This in particular points to the relatively small importance of the costs compared to the potential gains, reaffirming that it is mainly the foregone revenue and not so much the cost inefficiency that distinguishes regulated open access from optimal management (Homans and Wilen, 2005).

[15] The average cost per kg of cod obtained from the Lnnsomhetsunderskelser 1998-2002 were around 7 NOK. As these were not age-differentiated but the prices were, we have simply equated these to the average price and calculated the cost-adjusted-prices relatively as NOK 3 for cod of age 3-4, NOK 5 for cod of age 5-6, NOK 8 for cod of age 7-8, and NOK 10 for cod of age 9 and above

[16] We would like to thank an anonymous reviewer for pointing our attention to scrutinizing this issue.

The other optimization scenarios under this alternative set-up point in the same direction as the standard set-up: when only effort is a choice variable, we get pulse fishing and when only mesh size is a choice variable we get a mesh size around the same value as in the standard simulation (recall that effort is fixed at the same level of 11 million tonnage-days). Also the non-cooperative exploitation scenario is in line with the above intuition: effort is at its maximum value and harvesting is restrained via the mesh size. Only this time, the mesh size is inefficiently small, leading to a significantly reduced and truncated standing stock, and also steady state harvest and NPV are significantly lower.

All in all, the alternative simulations reinforce the conclusion that the mesh size is a choice variable of prime importance. Large gains can be had by targeting the right fish, or contrarily the "race to fish" in the dynamic game is played out also along the dimension of age. Conversely, the main results do not hinge on the assumptions about the cost structure.

5. Conclusion

Optimal management of the North-East Arctic cod, which takes the age- and gear-specific effects of harvesting decision into account, would lead to more than a doubling of the current economic gains while at the same time resulting in a much healthier fish stock. In contrast, a situation where two nations, each completely controlling their harvest, exploit the resource non-cooperatively would lead to a large loss of resource rents. Instead of a NPV of 116 billion Kroner, only a NPV of 67 billion Kroner could be earned over the next 50 years by each agent. An effort which is too high, and in particular a mesh size which is too small, implies a serious overuse of the resource. Its replenishing potential and the individual fish growth is not taken into account properly, a result which is remarkably similar to the current harvesting regime. Viewed in this light, it seems fair to conclude that today's inefficiency is largely due to the strategic structure in the Barents Sea.

Long-term forecasts of different management options are sensitive to a complex web of environmental (biological and economic) factors whose changes cannot be predicted for all practical purposes. Hence, these results are not to be taken as actual predictions of the future state but as comparisons of alternative management scenarios, provided all other things remain equal. Table 5 summarizes the results, where the steady-state values for the respective choice and state variables are reported for one of the two symmetric fleets.

[Table 5 here]

Note however, that the result that the Joint Commission agrees on what would have been the outcome even in absence of any channel of communication does not mean that the existence of the Joint Commission is superfluous. Quite to the contrary, the Commission serves many other purposes as well. It provides stability in an essentially unstable environment and most importantly, it establishes a platform from which measures that improve on the current situation might be taken. The age-structured modeling revealed that a significantly enlarged mesh size is key to enlarging the economic gain from the fishery. Focusing on this relatively simple measure might be more rewarding than trying to come to an agreement about fishing effort (Turvey, 1964).

In general, the analysis highlights the importance of age- and gear-specific modeling in fishery economics. The large gains of optimal management were possible because essentially the right fish were targeted while a non-cooperative and seemingly today's harvesting regime fail to do exactly this. An analytic understanding of the role of age-structure and gear selectivity for optimal and non-cooperative exploitation should shed new insights into the possibilities and limits to the management of today's marine resources. Exploring this potential will be the theme of work to come.

References

Aglen, A., Drevetnyak, K., Sokolov, K., 2004. Cod in the Barents Sea (North-East Arctic cod): a review of the biology and the history of fishery and its management. In: Bjordal, A., Gjøsæter, H., Mehl, S. (Eds.), Management Strategies for Commercial Marine Species in Northern Ecosystems. Institute of Marine Research, Bergen, Norway, pp. 27–39.

Armstrong, C. W., Flaaten, O., 1991. The Optimal Management of Transboundary Fish Resource - The Arcto-Norwegian Cod Stock. In: Arnason, R., Bjørndal, T. (Eds.), Essays on the Economics of Migratory Fish Stocks. Studies in Contemporary Economics. Springer, Berlin, pp. 137–152.

Armstrong, C. W., Sumaila, U. R., 2001. Optimal Allocation of TAC and the Implications of Implementing an ITQ Management System for the North-East Arctic Cod. Land Economics 77 (3), 350–359.

Arnason, R., Sandal, L. K., Steinshamn, S. I., Vestergaard, N., 2004. Optimal Feedback Controls: Comparative Evaluation of the Cod Fisheries in Denmark, Iceland, and Norway. American Journal of Agricultural Economics 86 (2), 531–542.

Başar, T., Olsder, G. J., 1995. Dynamic Noncooperative Game Theory. Academic Press, London.

Beverton, R., Holt, S. J., 1957. On the Dynamics of Exploited Fish Populations. Vol. 19 of Fishery Investigations Series II. Chapman & Hall, London.

Clark, C. W., 1980. Restricted Access to Common-Property Fishery Resources: A Game Theoretic Analysis. In: Liu, P. T. (Ed.), Dynamic Optimization and Mathematical Economics. Plenum, New York, pp. 117–132.

Dasgupta, P., Heal, G. M., 1979. Economic Theory and Exhaustible Resources. Cambridge University Press, Cambridge.

Diekert, F. K., Hjermann, D. Ø., Nævdal, E., Stenseth, N. C., 2009. Catching the Old

Fish: Optimal Harvesting Policies for North-East Arctic Cod. unpublished manuscript.

Dockner, E., Jørgensen, S., Long, N., Sorger, G., 2000. Differential Games in Economics and Management Science. Cambridge University Press, Cambridge.

Fiskeridirektoratet, 1998-2002. Lønnsomhetsundersøkelser for helårsdrivende fiskefartøy. Budsjettnemnda for fiskenæringen, Fiskeridirektoratet (Directorate of Fisheries), Bergen, Norway.

Fudenberg, D., Tirole, J., 1991. Game Theory. MIT Press, Cambridge, Mass.

Guttormsen, A. G., Kristofersson, D., Nvdal, E., 2008. Optimal management of renewable resources with darwinian selection induced by harvesting. Journal of Environmental Economics and Management 56 (2), 167–179.

Halliday, R. G., Cooper, C. G., Fanning, P., Hickey, W. M., Gagnon, P., 1999. Size selection of Atlantic cod, haddock and pollock (saithe) by otter trawls with square and diamond mesh codends of 130-155 mm mesh size. Fisheries Research 41 (3), 255–271.

Hannesson, R., 1975. Fishery Dynamics: A North Atlantic Cod Fishery. Canadian Journal of Economics 8 (2), 151–73.

Hannesson, R., 1993. Bioeconomic Analysis of Fisheries. Fishing News Books, Oxford.

Hannesson, R., 1997. Fishing as a Supergame. Journal of Environmental Economics and Management 32 (3), 309–322.

Hannesson, R., 2006. Sharing the Northeast Arctic Cod: Possible Effects of Climate Change. Natural Resource Modelling 19 (4), 633–654.

Hannesson, R., 2007. Cheating about the cod. Marine Policy 31 (6), 698–705.

Hardin, G., 1968. The Tragedy of the Commons. Science 162 (3859), 1243–1248.

Hjermann, D. Ø., Bogstad, B., Eikeset, A. M., Ottersen, G., Gjøsæter, H., Stenseth, N. C., 2007. Food web dynamics affect Northeast Arctic cod recruitment. Proceedings of the Royal Society B: Biological Sciences 274 (1610), 661–669.

Homans, F. R., Wilen, J. E., 2005. Markets and rent dissipation in regulated open access fisheries. Journal of Environmental Economics and Management 49, 381–404.

ICES, 2008. Report of the Arctic Fisheries Working Group (AFWG). Tech. rep., International Council for the Exploration of the Sea (ICES), Copenhagen.

Kaitala, V., Lindroos, M., 2007. Game theoretic applications to fisheries. In: Weintraub, A., Bjørndal, T. (Eds.), Handbook of operations research in natural resources. Springer, Ch. 11, pp. 201–216.

Kugarajh, K., Sandal, L., Berge, G., 2006. Implementing a Stochastic Bioeconomic Model for the North-East Arctic Cod Fishery. Journal of Bioeconomics 8, 35–53(19).

Kvamme, C., 2005. The Northeast Arctic cod (Gadus morhua L.) stock: Gear selectivity and the effects on yield and stock size of changes in exploitation pattern and level. Ph.D. thesis, Department of Biology, University of Bergen.

Levhari, D., Mirman, L. J., 1980. The Great Fish War: An Example Using a Dynamic Cournot-Nash Solution. The Bell Journal of Economics 11 (1), 322–334.

Millar, R. B., Fryer, R. J., 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. Reviews in Fish Biology and Fisheries 9 (1), 89–116.

Nævdal, E., 2003. Solving continuous optimal control problems with a spreadsheet. Journal of Economic Education 34 (2), 99–122.

Ottersen, G., 2008. Pronounced long-term juvenation in the spawning stock of arcto-norwegian cod (gadus morhua) and possible consequences for recruitment. Canadian Journal of Fisheries and Aquatic Sciences 65 (3), 523–534.

Ottersen, G., Hjermann, D. Ø., Stenseth, N. C., 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (gadus morhua) stock. Fisheries Oceanography 15 (3), 230–243.

Sandal, L. K., Steinshamn, S. I., 2002. Optimal age-structured harvest in a dynamic model with heterogenous capital. Working Paper SNF 84/02, Institute for Research in Economics and Business Administration (SNF).

Sandberg, P., Bogstad, B., Rottingen, I., 1998. Bioeconomic advice on TAC - the state of the art in the Norwegian fishery management. Fisheries Research 37 (1-3), 259–274.

Shepherd, J., Pope, J., 2002. Dynamic pool models II: Short-term and long-term forecasts of catch and biomass. In: Hart, P. J., Reynolds, J. D. (Eds.), Handbook of Fish Biology and Fisheries. Vol. 2. Blackwell, Ch. 8, pp. 164–188.

Steinshamn, S. I., 1993. Torsk som nasjonalformue: En disaggregert modell. Working Paper SNF 61/93, Institute for Research in Economics and Business Administration (SNF), Bergen.

Stenseth, N. C., Rouyer, T., 2008. Destabilized fish stocks. Nature 452 (7189), 825–826.

Stokke, O. S., Anderson, L., Mirovitskaya, N., 1999. The Barents Sea Fisheries. In: Young, O. R. (Ed.), The Effectiveness of International Environmental Regimes - Causal Connections and Behavioral Mechanisms. MIT Press, Cambridge, Mass., pp. 91–154.

Sumaila, U. R., 1997a. Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock in the Barents Sea. Environmental and Resource Economics 10 (2), 147–165.

Sumaila, U. R., 1997b. Strategic Dynamic Interaction – The case of Barents Sea fisheries. Marine Resource Economics 12 (2), 77–94.

Tahvonen, O., forthcoming. Age structured optimization models in fisheries bioeconomics: a survey. In: Boucekkine, R., Hritonenko, N., Yatsenko, Y (Eds.), Optimal Control of Age-structured Populations in Economy, Demography, and the Environment. Routledge.

Turvey, R., 1964. Optimization and suboptimization in fishery regulation. The American Economic Review 54 (2), 64–76.

Yang, Z., 2003. Reevaluation and renegotiation of climate change coalitions–a sequential closed-loop game approach. Journal of Economic Dynamics and Control 27 (9), 1563–1594.

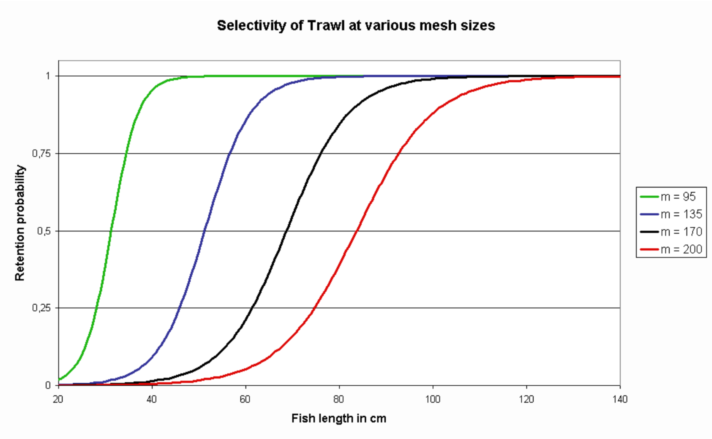

Fig. 1. Gear selectivity

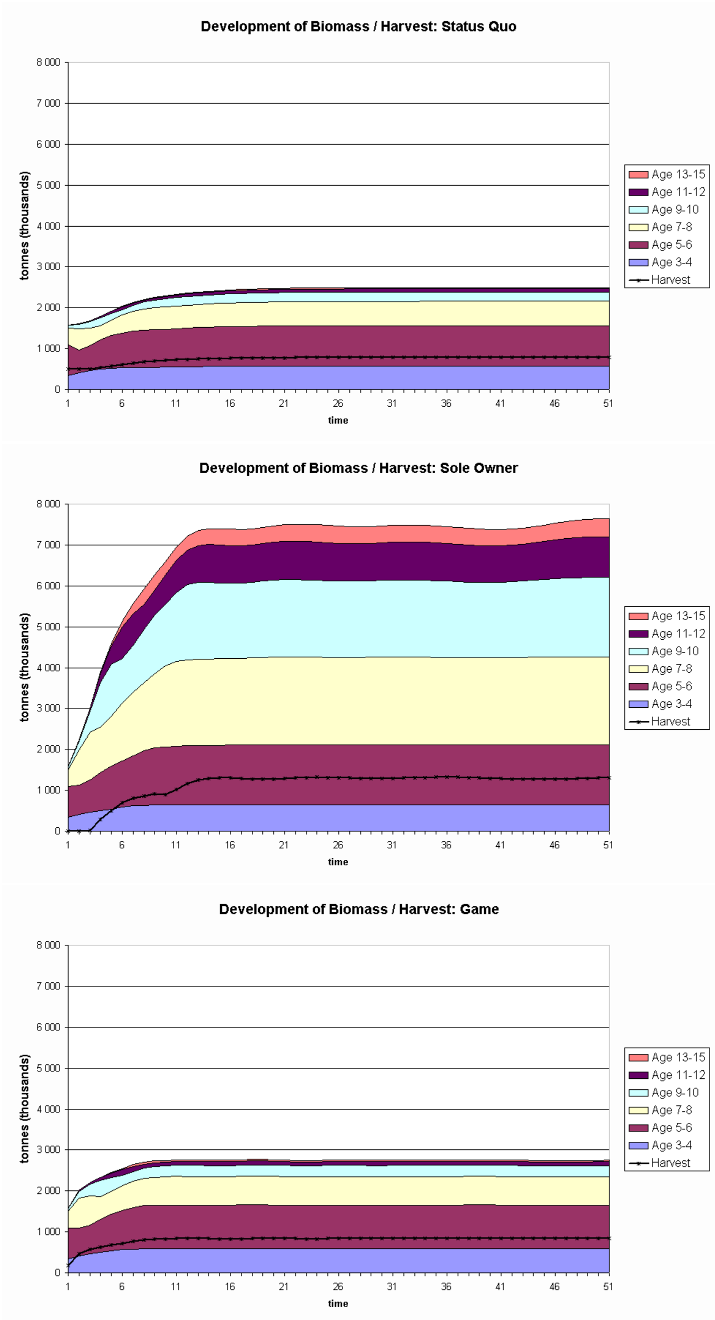

Fig. 2. Development of biomass and harvest for the three scenarios

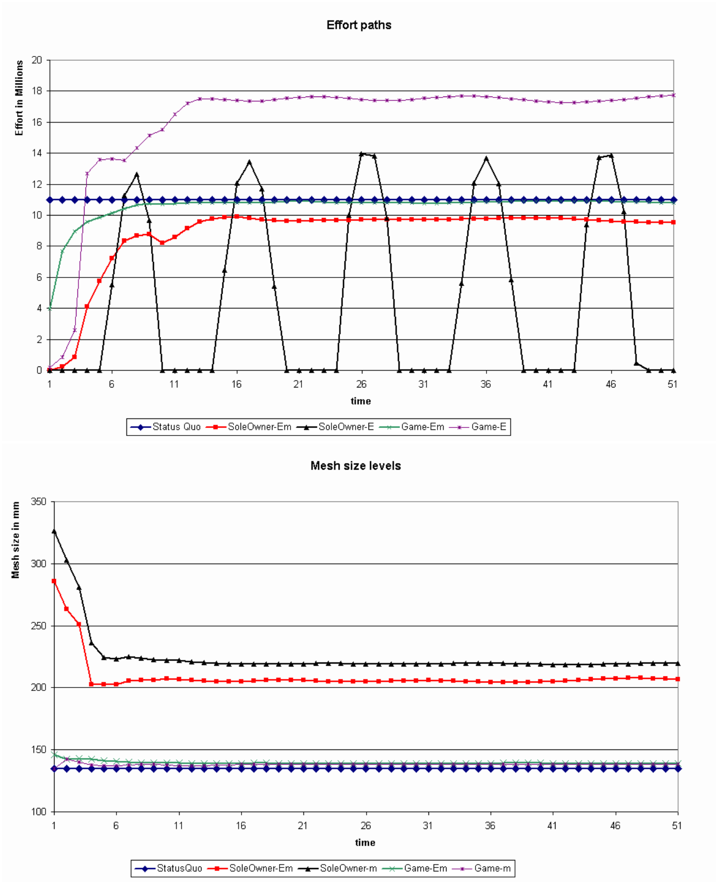

Fig. 3. Control paths of effort and mesh size

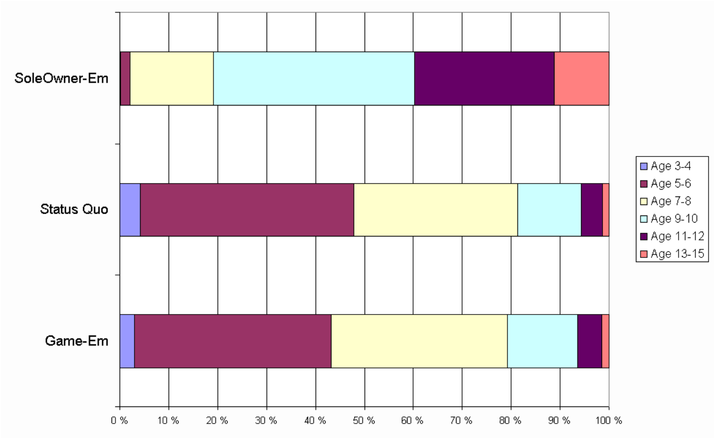

Fig. 4. Harvest composition

Age	3	4	5	6	7	8	9	10	11	12	13	14	15
l_a in cm	33,9	44,2	54,1	63,6	72,9	81,9	90,8	99,7	108,6	117	125,5	133,9	142,4
w_a in kg	0,36	0,69	1,31	2,20	3,36	4,78	6,46	8,39	10,56	12,99	15,67	18,60	21,77
mat_a	0,01	0,02	0,07	0,21	0,47	0,75	0,90	0,97	0,99	1,00	1,00	1,00	1,00

Table 1
Biological Parameters

Age	3	4	5	6	7	8	9	10	11	12	13	14
p_a in NOK	10	10	13	13	15	15	17	17	17	17	17	17

Table 2
Price at age

Simulation scenario	**Control variables**
StatusQuo	none, current effort and mesh size levels given
SoleOwner-Em	choose optimal cooperative effort and mesh size
SoleOwner-m	current effort given, choose optimal cooperative mesh size
SoleOwner-E	choose optimal cooperative effort, current mesh size given
Game-Em	choose non-cooperative effort and mesh size
Game-m	optimal cooperative effort given, choose non-cooperative mesh size
Game-E	choose non-cooperative effort, optimal cooperative mesh size given

Table 3
Overview of simulation scenarios

Russia	Norway			
	cooperative E and cooperative m	non-cooperative E and cooperative m	cooperative E and non-cooperative m	non-cooperative E and non-coop. m
cooperative E and cooperative m	116 ; 116	76 ; 139	63 ; 148	42 ; 160
non-cooperative E and cooperative m	139 ; 76	95 ; 95		
cooperative E and non-cooperative m	148 ; 63		79 ; 79	
non-cooperative E and non-coop. m	160 ; 42			67 ; 67

Table 4
Illustration Game scenarios (Payoff: NPV in billion NOK)

	Status Quo	*SoleOwner-Em*	*Game-Em*
NPV *in billion NOK*	55	116	67
Harvest *in thousand t*	392	647	418
Effort *in million units*	11	9,7	10,8
Mesh size *in mm*	135	206	139
Stock biomass *in thousand t*	2 493	7 468	2 751

Table 5
Summary of simulation results