Spare the Young Fish: Optimal Harvesting Policies for North-East Arctic Cod

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Abstract   The North-East Arctic cod (*Gadus morhua*) fishery, as most other commercial fisheries, is wasting the larger part of its potential. Examining a detailed multi-cohort, multi-gear bioeconomic model, we show that the cause is rather a too small mesh size than excessive effort. Although internationally and nationally managed by quota allocations and regulations, the current exploitation pattern implies that essentially the wrong fish are targeted. Catching older and heavier fish could double the fishery's Net-Present-Value. This increases harvested biomass while it reduces the number of fish removed from the ocean, highlighting the importance of age- and gear-specific modeling. Moreover, optimal harvesting policies would also lead to a much more robust and abundant cod stock.

Keywords   Age-structure · Bioeconomics · Gear selectivity · North-East Arctic cod · Optimal harvesting policies

1 Introduction

Atlantic cod (*Gadus morhua*) is currently being threatened by over-fishing. Overall catches that once have been rich are declining, and some fisheries had to be closed as stocks have collapsed. The fish stock of the Barents Sea, the North-East Arctic (NEA) cod, is one of the few cod stocks in a "reasonably good condition" (Fiskeri og Kystdepartementet FKD 2008). Nevertheless, scientific analysis has repeatedly shown that the harvesting pattern is "hugely

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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 shifted towards younger age classes (ICES 2006; Ottersen 2008).

Acknowledging the age-structure of long-lived fish stocks is central to its optimal management, yet it is often neglected in bioeconomic analyses. By example of an interdisciplinary model of the NEA cod fishery, we show that mesh size is a control variable which is at least as important as effort. Optimal harvesting policies could dramatically increase the economic gains obtainable from the resource. Moreover, this would lead to a significantly older, healthier, and more productive fish stock. The Net-Present-Value (NPV) of the fishery could be more than doubled, even when effort is fixed to its current level and only selectivity is allowed to vary. Conversely, choosing only effort and holding mesh size constant at today's regulation would still yield a significant improvement over the status quo, but would imply pulse fishing as an optimal response.

When modeling a fishery, one faces an important trade-off with respect to the detail of the underlying biological system. Aggregated (or "lumped parameter") models have the advantage of being analytically more tractable and being hence more readily applied in a nonlinear stochastic setting (Getz and Haight 1989). However, it has been argued that fishery economics has had a limited impact on actual fisheries management due to the overly simplifying properties of the models employed (Wilen 2000). Furthermore, it is becoming increasingly clear that summarizing the fish stock by one or two variables leads in most cases to unacceptable large deviations in optimal policy prescriptions (Tahvonen 2008; Krysiak and Krysiak 2002). Not only "reproductive overfishing", but also "growth overfishing", where inefficiently small specimen are targeted, has to be avoided. Moreover, high fishing pressure necessarily has ecological effects, i.e. it changes the stock's demography such as abundance and age/size distribution (Stenseth and Rouyer 2008), but it might also have evolutionary effects, changing genetically based life-history traits such as the stocks maturation pattern (Guttormsen et al. 2008; Jørgensen et al. 2007; Marshall and Browman 2007). More complex, detailed models are needed to take account of these qualitative changes that shape the resource dynamics. Consequently, there has been a growing interest in using age-structured and stage-based models in empirical resource economics (Pintassilgo and Duarte 2002; Smith and Wilen 2003; Massey et al. 2006; Grafton et al. 2007; Smith et al. 2008).

Most importantly, an age-structured model allows not only to answer how many fish should be harvested, but also which fish should be harvested. In general, there exists a substantive literature on optimal management of age-structured populations, mainly from mathematics and biology (see e.g. Brokate 1985; Getz and Haight 1989; Murphy and Smith 1990, and the references therein). Tahvonen (2009) is a pioneering analytic approach from an economic perspective. But for the general analysis of Turvey (1964) and Smith (1969), the question of optimal gear selectivity has received surprisingly little attention. Most contributions deal with this issue from a more technical perspective of fisheries sciences (Allen 1953; Beverton and Holt 1957; Garrod and Jones 1974; Huson et al. 1984; Tyutyunov et al. 1993; Helser et al. 1996; Kvamme 2005; Katsukawa 2005), where mainly the effects of different mesh sizes on yields are simulated. The only explicitly economic optimization is from Stollery (1984), who assumes perfect selectivity and provides a steady-state analysis.

In the following, we will first give a general account of the trade-offs involved in choosing a selectivity pattern (Sect. 2), and then provide a detailed model of the North-East Arctic cod fishery (Sect. 3) as a quasi-realistic numerical example. To the best of our knowledge, this paper is the first interdisciplinary approach to the optimization of age- and gear-specific harvesting policies of a fishery over a significant time horizon. An important feature of our study is that it rests upon an ecological model which has been derived through statistical analysis

of available time-series data from the Barents Sea system (Hjermann et al. 2007). It builds on a density-dependent recruitment function incorporating the effects of ambient temperature, capelin abundance, and cannibalism. The model specifies the average characteristics of a given cohort and allows effort and the age-specific selectivity of different gears to be choice variables. The results of the simulations are then presented and discussed in Sect. 4. Due to the fundamental uncertainties involved in marine systems, they can perhaps best be interpreted as *ceteris paribus* comparisons of different management scenarios. Yet, one thing transpires clearly: the importance of adapting the mesh size to the fishery at hand—in this case a significant enlargement from today's 135 mm to roughly 202 mm. By combining biology with economics, we are able to show that profits from the fishery could be dramatically enhanced. Optimization shifts the exploitation pattern towards older and heavier fish, which increases the harvested biomass while reducing the number of fish removed from the ocean. We therefore present not only results that extend the knowledge about the dynamic impacts of different management scenarios, but we also present results that are policy relevant.

2 The Effect of Gear Selectivity

It has long been held in resource economics that the general problem of multi-cohort harvesting is analytically unsolvable (Clark 1990). Recently, Tahvonen (2009) has shown that this might have been overly pessimistic (see also Wilen (1985) or Getz and Haight (1989) for good introductions). Here we motivate the significance of gear selectivity in broad terms. The fundamental questions are which fish to harvest and how many fish to harvest.

Imagine that a number of fish of all the same age are put in a pond. Suppose that the number of fish declines due to natural mortality, but the individual fish gain weight with age. Consequently, the overall biomass of fish in the pond will grow in the beginning but level out and decrease after some time. If harvesting is costless, it is clear that all fish should be caught and the problem reduces to the question when this should be done. The maximum value of this cohort will depend on the specific growth function and on the price per kg of fish (which may also be an increasing function of age/size).

Obviously, the optimal timing of harvest will be altered if we have a time-preference, if harvesting is not costless, or if it is not possible to take all fish at once. Given that any of these factors play a role, harvesting should begin earlier in time and it should be spread over some interval (Allen 1953; Wilen 1985). Note that in our imaginary pond, time directly translates into age of the cohort. Also the value of the stock is the value of that cohort.

If we would now introduce a new cohort in the beginning of each period, then the value of the stock would be the sum of all the cohorts in the pond and time would begin to matter. If it were possible to perfectly select the first age at capture (*knife-edge selectivity*), and all conditions remain in equilibrium, then the problem is identical to the single-cohort problem (Beverton and Holt 1957). The gear should be calibrated such that the fish are targeted in the instant they have reached optimal value. But what should be done if the gear is completely non-selective? The best is then to empty the pond and let the stock replenish before the pond is emptied again (*pulse fishing*). Because it is not possible to single out the cohort with the highest value, growth overfishing is avoided by letting old and valuable cohorts reach an adequate proportion of the overall stock (Tahvonen 2009).[1]

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[1] A formal proof that periodic fishing produces a greater average yield than continuous catch given non-selective gear can be found in (Clark 1990, p. 299).

Now in real life, there is neither knife-edge selectivity nor completely non-selective gears. Unlike in the imaginary pond, fish stocks consist of many cohorts that have been subject to environmental fluctuations and fishing in varying degrees. Moreover, harvesting has a profound impact on the reproduction potential of the stock. Also, harvesting is not a one-dimensional choice variable, but it involves many aspects. At the crudest level, it is effort and the selective properties of the gear that together determine which and how many fish are caught. With these real-world complexities taken into account, models rapidly lose their tractability.

Nonetheless, the reasoning from the thought experiment carries over: The better it can be controlled which fish are targeted, the more profitable it becomes to continually harvest part of the stock. Simultaneously, the more effort is applied, the larger should be the mesh size. For every level of effort, there is a mesh size that maximizes equilibrium profit or yield. This mapping is called the *eumetric yield curve* (Beverton and Holt 1957). However, there is not necessarily an optimal continuous level of effort for every mesh size: The smaller the mesh size, the more age-classes are targeted indiscriminately. Below a certain mesh size it becomes worthwhile to invest great effort to harvest as much as possible and start afresh afterwards. Instead of a steady harvesting, a cyclical exploitation pattern emerges.

That increasing the age at first capture may indeed be more effective than an effort control (Katsukawa 2005) follows from a simple observation: Consider a steady state of the dynamic system where too much effort and a too small mesh size is applied. Then reducing effort is beneficial because fishing mortality is reduced for all age-classes, and the fish stock becomes more abundant. However, there would still be inefficiently small fish in the nets. In contrast, increasing the mesh size directly avoids growth overfishing *and* it ensures that each cohort is more abundant when it reaches the age at first capture, since it has not been subjected to fishing mortality before.

The simulations of our model show both that the current mesh size in the NEA cod fishery is so maladapted that it produces pulse fishing and that a move to the eumetric yield curve alone could more than double the economic gains of the fishery (Sect. 4.2). The different forms of gear selectivity have a tremendous effect on the exploitation pattern. Ultimately, this is the result of not seeing fish as a uniform mass but acknowledging that stock are composed of many fish with individual characteristics.

3 The North-East Arctic Cod Fishery

The Barents Sea is the feeding and nursery area of the North East Arctic cod stock. The mature fish migrate in winter/spring to their spawning grounds along the Norwegian coast (see Fig. 1) where they are targeted by the Norwegian coastal fleet. Russian, Norwegian, and international trawlers target the fish in the Barents Sea. Although the fishery is conducted all year, it has a distinct seasonal pattern where most fishing effort is applied in the first half of the year.

The fish stock is jointly managed by Russia and Norway. Despite the fact that more and larger fish thrive in Norwegian waters, Russia and Norway divide the annual total allowable catch quota (TAC) equally among themselves (after traditionally allocating 10–15% to third countries). This sharing rule has the advantage that it frees the negotiations from allocational bargaining (Stokke et al. 1999). In addition to the total quota, the fishery is regulated by a variety of technical regulations on gear, the minimum size of fish, a ban on discards, temporarily closed areas etc. The current minimum mesh size for trawl is 135 mm in Norwegian

Fig. 1 Distribution of NEA cod.
Source: FKD (2008)
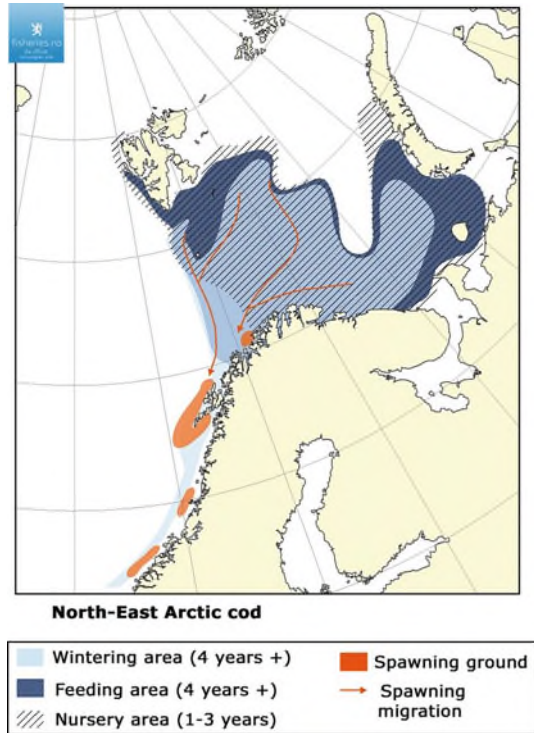
waters and 125 mm in Russian waters. It is planned that a common mesh size of 130 mm will be applied throughout the Barents Sea from 2011 on (FKD 2009).

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. 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). The interaction between the different participating fleets is analyzed by Hannesson (1978), Steinshamn (1994), and Sumaila (1997). Closely related, the effect of cannibalism and inter-species competition on optimal harvesting and fleet selection is studied by Armstrong (1999) and Sandal and Steinshamn (2002). In contrast to these studies, our work does not need to rely on restrictive assumptions with respect to the selectivity of different fleets. 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. (2010) and Hannesson (2007a).

A model of this fishery requires a series of simplifications and abstractions, highlighting its general exemplary character rather than its specific numerical specification. For example, the Norwegian fleet is internally managed by a system of individual vessel quotas, that assign a share of the total quota to each vessel. We abstract from modeling the quotas explicitly and focus on effort and mesh size as separate control variables that together determine the harvest. As we are seeking to provide an estimate of possible economic gains, we focus on the maximization of the Net-Present-Value (NPV) as our metric. We presume the existence of a *sole-owner* with complete control over resource exploitation. In general, our model should be taken as an exemplary comparison of alternative management scenarios and not interpreted as

Table 1 Biological parameters

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	109	117	126	134	142
w_a in kg	0.36	0.69	1.31	2.20	3.36	4.78	6.46	8.39	10.6	12.9	15.7	18.6	21.8
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

actual predictions of future states. The latter would be futile, not the least because long-term forecasts are sensitive to a complex web of biological and economic factors, whose changes cannot be predicted for all practical purposes. Consequently, we condition the biological model on average values, consider only short run cost, and abstract from changes in prices or technology over time.

3.1 Biological Model

As a living resource, the NEA cod stock depends on the conditions of its biotic and abiotic environment. Temperature and salinity of the water, the inflow of warm currents and climatic factors fluctuate strongly in this sub-arctic region. The food web is relatively simple in that it consists of only a few species at the various trophic levels. Cod is a top predator, feeding along the polar front during summer-autumn and spawning on the Norwegian coast (especially around Lofoten) in March–April (Nakken 1998). Cod larvae drift with Atlantic currents into the Barents Sea. Predatory cod follow the schools of capelin to the coasts of Northern Norway and Northwestern Russia. Whenever there is not enough capelin available, the older cod turn to juveniles as a source of food (i.e., cannibalism). Such cannibalistic cod mainly consists of 3–6-year-old immature cohorts (Hjermann et al. 2007). These fish do not migrate to the spawning grounds yet and therefore share much the same area as juvenile cod for the whole year. Largely the same circumstances determine length/weight growth and survival probability of cod after its recruitment to the fishery at the age of 3 years (Hjermann et al. 2004).

The biological model describes the number of cod ($N_{a,t}$) of a given cohort of age a at time t, its average individual length-at-age l_a, weight-at-age w_a, and maturity probability mat_a. Somatic growth and maturation are assumed to depend only on age, not on food supply or temperature. The values result from regressions on ICES data, and are given as time-independent parameters (Table 1).[2]

Cod keeps on growing with age even if energy is also allocated to reproduction after maturation, hence, 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

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[2] All regressions have been made in "R" (http://www.r-project.org). The parameters for length-at-age l_a are derived from a separate regression for age three and a regression for age four and above. For the length at age three, the estimated intercept was 30.61 [standard error (SE) = 1.15] and the coefficient for capelin biomass was 0.0014 [SE = 0.00043], and the R-squared was 0.29. For the length at age four and above, the best model (yielding an R-squared of 0.97) was one that included the length of the previous year (coefficient of 0.77 [SE = 0.05]), the age (1.90 [SE = 0.53]), and the capelin biomass (0.00036 [SE = 0.00012]) in addition to the intercept (9.55 [SE = 0.97]). The parameters for weight-at-age w_a stem from a regression on age (−0.53 [SE = 0.12]), length (−0.026 [SE = 0.014]), the biomass of capelin (−0.000069 [SE = 0.00006]), and an interaction effect of age and length (0.015 [SE = 0.0016]). The intercept is then (1.47 [SE = 0, 57]) and the model can explain 96% of the variation in the data. Finally, the parameters for the maturity schedule mat_a are obtained by fitting a general linear model to the logistic function, with the variables length (coefficient estimate 0.13 [SE = 0.025]), temperature (0.92 [SE = 0.49]), and a constant term (−13.32 [SE = 2.87]).

age of 12 years (ICES 2006). Nevertheless, it is important to include more age-classes in the bioeconomic 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.[3] The total biomass of the stock is the sum of the biomass of each age group: $X_t = \sum_{a=3}^{15} N_{a,t} \cdot w_a$ (number of fish multiplied with their average individual weight). The spawning stock biomass is defined as the sexually mature part of the stock: $SSB_t = \sum_{a=3}^{15} N_{a,t} \cdot w_a \cdot mat_a$ (the age-specific biomass multiplied with the probability that the cohort has matured and summed over all ages).

The function for the recruitment of fresh cod to the fishery is developed in Hjermann et al. (2007). The model assumes that the cod's spawning stock biomass (SSB) and recruits are linked by the Beverton-Holt relationship $f \cdot SSB / (1 + g \cdot SSB)$. This relationship is then modified by a coefficient for the positive effect of temperature ($temp$) and the negative effect of the ratio between cannibalistic cod ($X_{can,t}$) and capelin (cap).[4] The resulting recruitment function is:

$$\log N_{3,t} = \log\left(\frac{f \cdot SSB_{t-3}}{1 + g \cdot SSB_{t-3}}\right) + c \cdot temp - d\left(\frac{X_{can,t-2} + X_{can,t-1}}{cap}\right) \tag{1}$$

The number of cod develops according to the difference equation:

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

where M is the instantaneous natural mortality, conventionally set to 0.2 for all cohorts (ICES 2006), and $F_{a,t}$ is the effective age-specific fishing mortality. Bearing in mind the seasonal exploitation pattern of the NEA cod fishery, fishing and natural mortality are modeled to 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 F has a direct impact on the survival rate, but it also has an indirect impact on the stock dynamics via the spawning stock biomass and via the effect of cannibalism. The term "effective fishing mortalitys" 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. Here fishing mortality is the probability that fish of a certain cohort is caught in a given year. It depends on the intensity of fishing, presumably proportional to effort, and the selectivity of the gear (see Sect. 3.2.1). The fishing mortality therefore constitutes the link between the economic and the biological part of the model.

3.2 Economic Model

We concentrate on the three most distinguishable sub-fisheries which differ in their harvest function and cost structure. For simplicity it is assumed that conditional on fish size, they face the same price schedule. The Lofoten fishery (denoted *lof*) targets the mature stock in the

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[3] A cohort of cod reaches its maximum biomass around 11–12 years and few individuals would survive up to an age of 15 even in absence of fishing pressure.

[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 2006). More precisely, it is a good proxy for the general environmental conditions that determine the survival probability of the larvae during its first 5 months (Ottersen and Loeng 2000). The average values of temperature and capelin biomass used in the simulations are 2,381 thousand tons and 3, 9152 ° Celsius respectively. According to the Beverton-Holt function, recruitment tends to f as the spawning stock goes to zero and recruitment asymptotically tends to f/g as the spawning stock grows large. The estimated parameters are: $\log(f) = -1.12[SE = 0.74]$, $\log(g) = -4.68[SE = 0.77]$, $c = 0.70[SE = 0.18]$, $d = 0.16[SE = 0.07.]$

Table 2 Price at age

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

spawning grounds (in Lofoten and elsewhere on the Norwegian coast). It consists of rather small boats (8–20.9 m) using gillnet and handline. Norwegian trawlers (denoted *Ntrl*) and Russian trawlers (denoted *Rtrl*) fish in the Barents Sea. The profits of fleet j in a given year t are determined by:

$$\pi_t^j = \sum_{a=3}^{15} p_a \cdot H_a \left(X_t, E_t^j, E_t^{-j}, m_t \right) - c \left(E_t^j \right) \tag{3}$$

$c(E_t^j)$ represents the cost of applying effort E for fleet j. $H_a(X_t, E_t^j, E_t^{-j}, m_t)$ is the age-specific harvesting function which depends on the state of the resource X_t, on the amount of own effort E_t^j, the effort of the other two fleets E_t^{-j} and on the gear selectivity which is influenced by the choice of mesh size m (Sect.. 3.2.1). Price p_a is age-specific as older and heavier fish receive a higher price per kg (Table 2).[5]

3.2.1 Harvest Function

The harvest function $H_{a,t}(\cdot)$ tells how many fish of age a are caught at time t. Conceptually, it is simply the biomass times the age-specific fishing mortality $F_{a,t}^j$.

$$H_{a,t} = X_{a,t} \cdot F_a(E_t^j, E_t^{-j}, m_t) \tag{4}$$

This fishing mortality $F_{a,t}^j$ for $j = lof, Ntrl, Rtrl$ is fully specified in Eq. (7a–c). For sake of exposition, write it as $F = r(1 - e^{-qE})$. It displays decreasing returns to scale and contains two concepts: First, the gear specific selectivity $r^j(l_a, m_t)$, defined as "the probability that a fish of length $[l_a]$ is captured, given that it contacted the gear $[j$ with mesh size $m_t]$" (Millar and Fryer 1999, p.92). The second concept is the fleet specific catchability, summarized by the coefficient q^j. The exploitation level (i.e. how many fish caught) is determined by the amount of effort, given in the unit *tonnage-day* of a standardized vessel. It is assumed to take values in $[0, \infty)$. The exploitation pattern (which fish are caught) is determined by the location of fishing and mainly by the gear which is being used. For a given type of gear its selectivity can be influenced by the mesh size m which is presumed to take in the range 60–300 mm. These bounds are somewhat arbitrary, but include all realistic mesh size values.

The shape of the selectivity pattern $r^j(l_a, m_t)$ varies between the different gear types. 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, and the

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[5] The minimum prices from the Norwegian fishermen's sales organization (Norges Råfiskelag 2007) 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.

gear selectivity curve is of *S*-shaped form. Halliday et al. (1999) have gathered data from selection studies of different mesh sizes for cod and established the relationship between mesh-size *m* in mm, the selection range (the steepness of the curve), and the length of a fish which is retained in the net with 50% probability (the inflection point). Kvamme (2005) found the logistic curve to fit best to the data, so that the following selectivity curve for trawl nets is established:

$$r^{trl}(l_a, m_t) = \left(1 + \exp\left(\frac{-2.2 \cdot (l_a - 0.499\, m_t + 16.105)}{0.112\, m_t - 4.335}\right)\right)^{-1} \tag{5}$$

Lofoten vessels mostly use gillnets but also handline and longline. Gillnets entangle the fish that swim into them. While sufficiently small fish pass through the meshes, sufficiently large fish do not penetrate far enough to become wedged. Handlines and longlines lure the fish with baits and the bait and hook size is thought to be optimal only for a limited range of cod sizes. Therefore the selection curve of conventional gears is usually assumed to be bell-shaped. Huse et al. (2000) found the gamma curve to fit best to catch data.

$$r^{lof}(l_a, m_t) = \left(\frac{l_a}{0.519\, m_t}\right)^{47.956} \cdot \exp\left(47.956 - \frac{l_a}{0.011\, m_t}\right) \tag{6}$$

In general, a larger mesh-size *m* moves the selectivity curves to the right, but it also makes the selection range larger, so that the curves get flatter. They are plotted for various mesh sizes in Fig. 2.

Furthermore, the catchability coefficient q^j contains that part of fishing mortality which is not captured by the gear selectivity. It is influenced by the composition of the fishing fleet, the effort and skill of the fishermen, as well as the distribution and behavior of the fish (Kvamme 2005). Technically, it is a constant of proportionality that links the units of effort to the units of harvest. It is scaled so that the range of the selectivity curve is between zero and one (Getz and Haight 1989). 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 of 1998–2002 from ICES (2006), Eq. 4 is used to calibrate fleet specific catchability[6] as $q^{lof} = 3{,}87 \cdot 10^{-8}$ and $q^{Ntrl} = q^{Rtrl} = 1{,}94 \cdot 10^{-8}$.

A model which portrays the NEA cod fishery should take the spatial distribution of the stock into account, since Russia and Norway have sovereignty only in their territory. However, they concede each other the right to fish large parts of their quota in their respective zones (Stokke et al. 1999). For simplicity, it is therefore assumed that both trawler fleets have complete access to the entire biomass in the ocean. The Lofoten fleet is set up to first harvest exclusively on the mature biomass and what is left returns to the feeding grounds. The biomass in the harvest functions of the trawlers is therefore multiplied with the term $(1 - F_{a,t}^{lof})$. Furthermore, the fishing mortality of the trawler fleets is modified so that the sum of both trawler efforts in the exponent ensures that the combined mortality does not exceed 1. The last term assigns the respective share according to the fleet's effort:

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[6] 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.
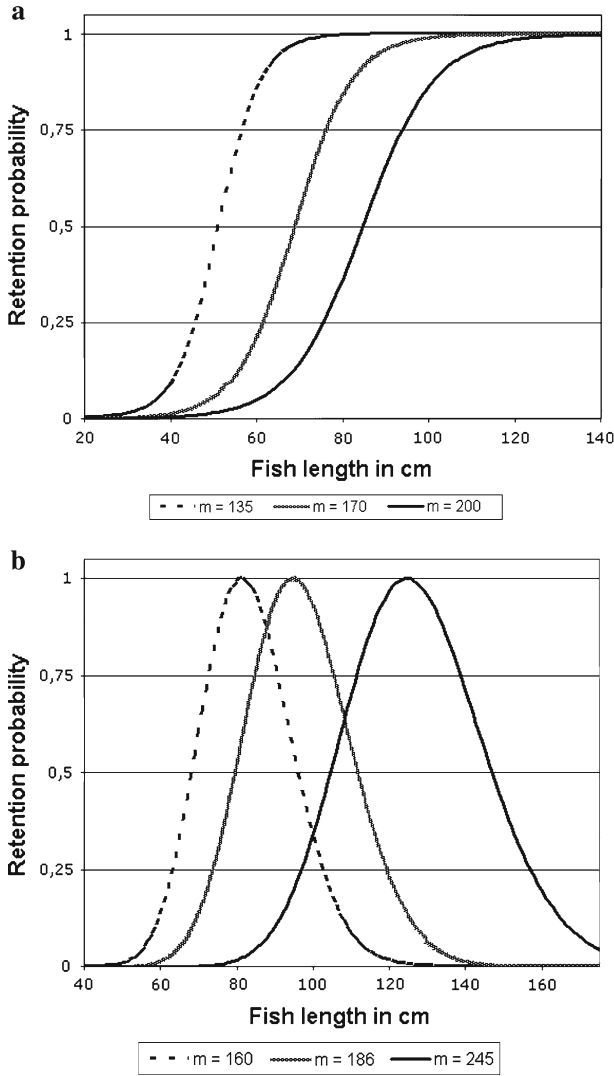
Fig. 2 Selectivity curves for different mesh sizes. **a** Trawl selectivity. **b** Gillnet selectivity

$$F_{a,t}^{lof}(E, m) = r^{lof}\left(l_a, m_t^{lof}\right) \cdot \left(1 - e^{-q^{lof} \cdot E_t^{lof}}\right) \tag{7a}$$

$$F_{a,t}^{Ntrl}(E, m) = \left(1 - F_{a,t}^{lof}\right) \cdot r^{trl}\left(l_a, m_t^{Ntrl}\right) \cdot \left(1 - e^{-q^{trl} \cdot \left(E_t^{Ntrl} + E_t^{Rtrl}\right)}\right) \cdot \frac{E_t^{Ntrl}}{E_t^{Ntrl} + E_t^{Rtrl}} \tag{7b}$$

$$F_{a,t}^{Rtrl}(E, m) = \left(1 - F_{a,t}^{lof}\right) \cdot r^{trl}\left(l_a, m_t^{Rtrl}\right) \cdot \left(1 - e^{-q^{trl} \cdot \left(E_t^{Rtrl} + E_t^{Ntrl}\right)}\right) \cdot \frac{E_t^{Rtrl}}{E_t^{Ntrl} + E_t^{Rtrl}} \tag{7c}$$

3.2.2 Cost Structure

The Norwegian Directorate of Fisheries annually publishes a survey of the profitability of fishing fleets where it specifies tonnage, days-at-sea, and cost for the average vessel in each category. On the one hand, this aggregation leads to a loss of variation which hence lowers the efficiency of estimation. On the other hand, it may "smooth out" out the inherently stochastic nature of fisheries data and hence measurement error (Grafton et al. 2006). As we were looking for but a rough estimate of the cost structure in the fishery, the data (Fiskeridirektoratet 1998–2002) was deemed sufficient.

$$c^j(E) = c_1^j E^2 + c_2^j \tag{8}$$

This function provided the best fit among several convex polynomial functions. The constant term c_2^j should not be interpreted as a fixed cost, but rather as a parameter that insures the best possible fit over the relevant effort interval. The cost fitted parameters in Norwegian Krones (NOK, in year 2000 value) were $c_1 = 6.5 \times 10^{-5}, c_2 = 2.86 \times 10^8$ for the Lofoten fleet, $c_1 = 5.8 \times 10^{-6}, c_2 = 1.79 \times 10^9$ for the Norwegian trawler fleet, and $c_1 = 5.2 \times 10^{-6}, c_2 = 1.61 \times 10^9$ for the Russian trawlers.[7]

3.3 Simulation

In light of the discussion in Sects. 1 and 2, the prospective gain from optimal management will be illustrated by a simulation scenario in which a hypothetical sole owner chooses the paths of effort E_t and mesh size m_t, so as to maximize the NPV of the fishery (*optimal harvesting*). The importance of gear selectivity is highlighted by contrasting the results from above to a scenario in which today's effort is taken as fixed and the optimal mesh size m_t is chosen (*only m_t optimal*), and to a scenario in which effort is chosen given today's mesh size regulations (*only E_t optimal*). Finally, the continuation of the current exploitation pattern serves as a benchmark against which optimal harvesting is compared. For this scenario, named *status quo*, the average values of effort and mesh size from 1998 to 2002 are employed as constants over the entire time horizon.

With exception of the *Status Quo* scenario, the objective is the maximization of the sum of discounted annual profits of the three fleets:

$$\max_{u_t} \sum_{t=0}^{T} \delta^t \cdot \left[\pi^{lof}(X_t, u_t) + \pi^{Ntrl}(X_t, u_t) + \pi^{Rtrl}(X_t, u_t) \right]$$

subject to: the biological system X_t; $\quad X_0 = $ given; and $u_t \in U \tag{9}$

- 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

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[7] There are no available data on Russian costs, but benefiting from the technical similarity between Russian and Norwegian trawlers, the latter cost-structure, weighted by a factor to account for differences in labor cost etc, is used for the former. In lack of an adequate foundation for estimating such a factor, 0.9 was arbitrarily chosen. The main results of the analysis are insensitive to various tested specifications of the cost function (see also Sect. 4.4).

horizon case.[8] Discounting with a rate of 5% (implying a discount factor δ of 0.9523) was introduced to include a rate of time preference.[9]

- The control region depends on the simulation scenario. For *only E_t optimal* in the second scenario: $U = E$ and $u_t = \{E_t^{lof}, E_t^{Ntrl}, E_t^{Rtrl}\}$, for *only m_t optimal* in the third scenario: $U = m$ and $u_t = \{m_t^{lof}, m_t^{Ntrl}, m_t^{Rtrl}\}$, and finally for *optimal harvesting*: $U = (E, m)$ and $u_t = \left\{E_t^{lof}, E_t^{Ntrl}, E_t^{Rtrl}, m_t^{lof}, m_t^{Ntrl}, m_t^{Rtrl}\right\}$. In all cases, U is convex since $E \in [0, \infty)$ and $m \in [60, 300]$.
- The biological system, summarized by X_t, is specified by the vector of age-class abundance with the recruitment function (1) giving the entry $N_{3,t}$, and the entries for $a = 4, \ldots 15$ according to the cohort development (2) as well as the weight, length, and maturity parameters summarized in Table 1. The initial state X_0 is given by the latest number assessment of ICES (2006).

The solutions have been obtained numerically by the "GRG Nonlinear Solver" from the Premium Solver Platform of Frontline Systems. This solver uses well established methods and is suitable for large-scale nonlinear optimization problems. Nevertheless, in order to ensure that the procedure did not report a local stationary point which was not the global optimum, we have run each simulation from ten random starting points in addition to starting from the status quo values.

All runs yielded qualitatively the same paths. After an initial phase of 15 years, state and control variables converge and do not change until the end of the time horizon was approached, when it was optimal to harvest down the biomass (effort and biomass values begin to change from year 65 on). The system can therefore safely considered to be close to the steady state in the interval from year 15 to 50 (due to the inevitable imprecision of numerical procedures, some fluctuations around the equilibrium are reported). See also Fig. 3 which displays the values of the effort paths over the entire time horizon of 75 years.

The cyclical harvesting pattern of the *only E_t optimal* scenario was similarly robust to random initial conditions, though it obviously did not yield steady state values. Instead, the average values over the 9–10 years periodic cycle are reported. The percentage standard deviation of the average NPV for the different runs was 0.02% for the *optimal harvesting* scenario, 0.3% for the *only E_t optimal* scenario, and 0.0000001% for the *only m_t optimal* scenario.

4 Results and Discussion

The main results of the different simulation scenarios are summarized in Table 3. Figure 4 displays the development of the stock biomass over the first 50 years. We will first compare the current exploitation pattern with a management strategy where both gear selectivity and effort are optimally chosen. We will then contrast the scenario where only mesh size is chosen with the scenario where only effort is chosen. Finally, we discuss the implications and sensitivity of our results.

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

[9] Even though a discount rate of 5% is rather high, this is advantageous for the simulation because it makes the distant periods less important for the NPV. The Norwegian Ministry of Finance (Finansdepartement 2008) is employing a discount rate of 4% and in larger Europe public investment are discounted at a similar rate.
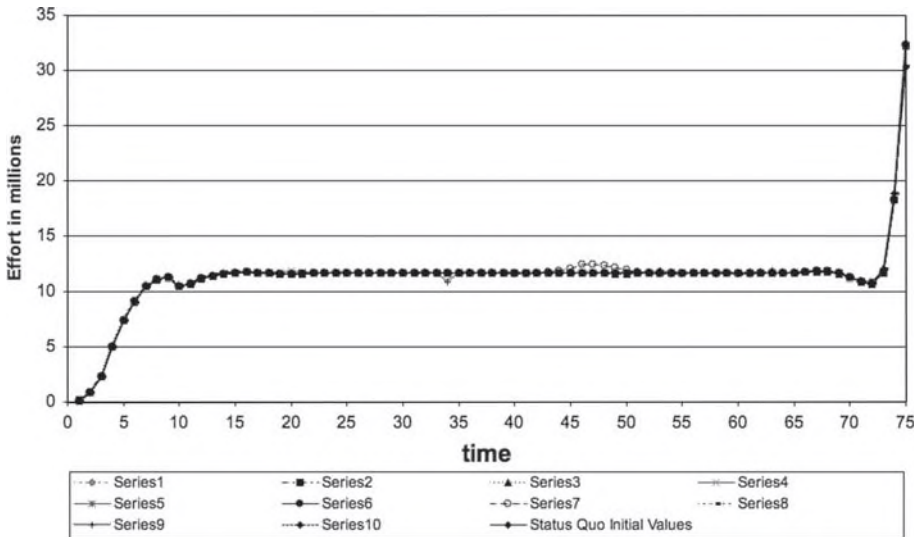
Fig. 3 Effort of Rtrl over time

**Table 3** Summary of results from different simulation scenarios

	Status quo	Optimal harvesting	Only E_t Optimal	Only m_t Optimal
NPV (in billion NOK)	70	155	119	147
Stock biomass (in thousand t)	2443	6041	4520*	6025
Harvest (in thousand t)	703	1022	785*	1039

* 9–10 years cyclical fishing pulses; average values over the cycle are reported for biomass and harvest

4.1 Comparison of Current and Optimal Management

In order to simulate a continuation of the current harvesting pattern, the average effort values from Fiskeridirektoratet (1998–2002) have been applied over the entire time horizon (12 million tonnage-days for the trawler fleets and 2 million tonnage-days for the Lofoten fleet). For the mesh size, the current regulation in Norwegian waters (135 mm) has been applied for the trawlers, and for the Lofoten fleet, the most common mesh size of 186 mm (Huse et al. 2000) was used. This *status quo* exploitation yields a Net-Present-Value of 70 billion Norwegian Krones (NOK, in year 2000 value). Since the model is deterministic, using the same effort allows rapid convergence (Fig. 4a).[10] More than half of the fish stock is younger than 6 years. The total biomass in steady state is under 2.5 million tons and the average harvest is around 700 thousand tons. Today's gear regulation of 135 mm for trawl nets means that fish above 60 cm are subject to the full fishing pressure (Fig. 2). Consequently, the harvested biomass consist mainly of inefficiently small fish (Fig. 5). Fish of age 9 and older sum up to only 18% of total harvest.

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[10] The observation that the biomass is indeed 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.
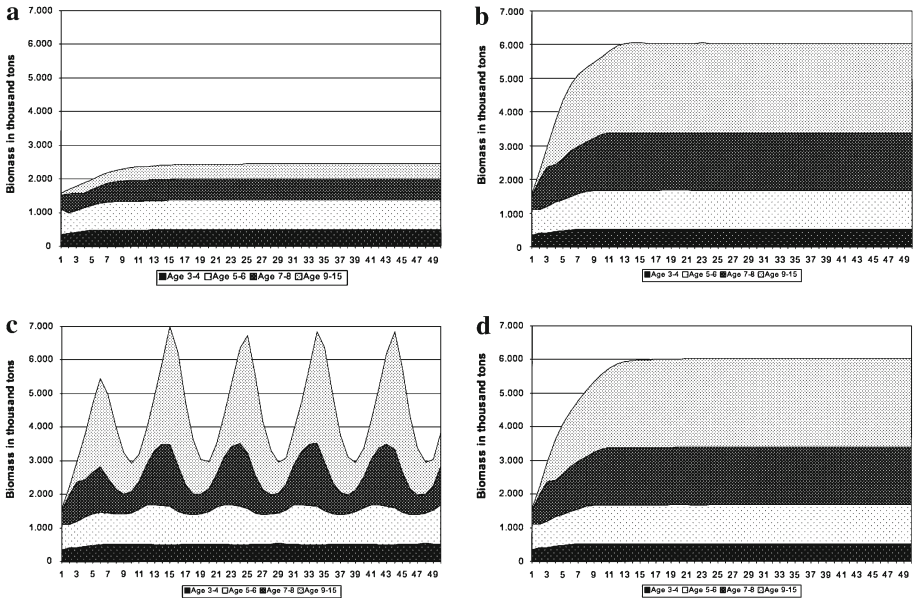
Fig. 4 Development of biomass and harvest for the different scenarios. **a** Status Quo. **b** Effort and mesh size are controls. **c** Effort is control variable. **d** Mesh size is control variable
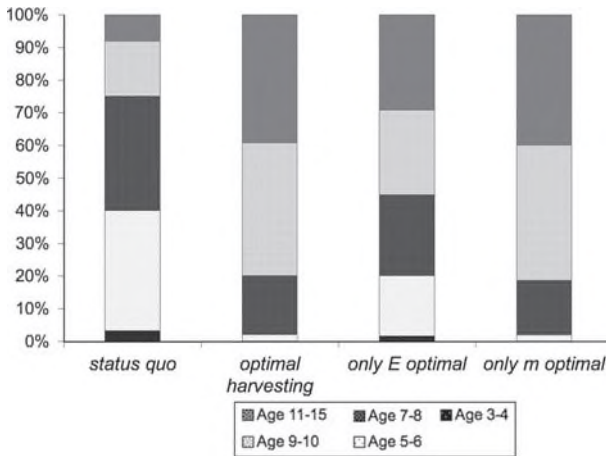
Fig. 5 Harvest composition

In contrast, optimal management yields a NPV of 155 billion NOK, more than twice as much as under the current regime. Essentially, this increase in profits is the result of fully exploiting the growth potential of the fish. To this end, enlarging the mesh size is more important than reducing effort. This is underlined by complimentary simulations, showing that the loss implied by shifting the gear selectivity by 10% from its optimal value is roughly 8 billion NOK, while the loss implied by shifting the optimal effort path by 10% is around 0.6 billion NOK.

As these gains can only be obtained if the proportion of old and large individuals is sufficient, the optimization implies an build-up phase of 4 years where little harvest is taken. After that, the fishery makes positive profit and the remaining fluctuations until year 15 serve to adjust the age-structure of the fish stock. Control and state variables are in the steady state for the rest of the reported time (Fig. 4b). Sustainable biomass is 6 million tons and 1 million tons are harvested annually in the equilibrium. The optimal effort level is 11.5 million tonnage-days for the Russian trawlers, 10.5 million tonnage-days for *Ntrl* and 1.5 million tonnage-days for the Lofoten fleet.

The optimal mesh size for trawlers is 202 and 236 mm for gillnets. From Table 2 and Fig. 2 it can be inferred that this means that fish above 85 cm are targeted. At this size, the fish are older than 8 years and the year-classes 9+ consequently make up 80% of the harvest. Intuitively, by targeting older and heavier fish, less fish have to be removed from the stock in order get the same volume of harvest. Optimal management that takes the selectivity pattern of the gear into account thus leads simultaneously to a higher harvest and a higher standing stock.

The altered age/size distribution of the stock could be important beyond concerns about profit: Older and heavier fish are better able to buffer adverse environmental fluctuations, which are presumably amplified by climate change (Ottersen 2006). Moreover, age-specific resource management would thus overcome the effect of "age-truncation" which is evident in many fisheries (Beamish et al. 2006), and which may lead to magnified fluctuations in fish stocks (Anderson et al. 2008). Therefore optimal management might reverse this trend, as long as harvesting has not resulted in evolutionary change (Stenseth and Rouyer 2008).

4.2 Controlling Only Effort Versus Controlling Only Selectivity

The relative importance of controlling gear selectivity is further highlighted by the simulations where only one policy variable could be chosen and the other was fixed to its status quo level. The *only E_t optimal* scenario, where only effort was a choice variable, yields a NPV of 119 billion NOK, while the *only m_t optimal* scenario yields a NPV of 147 billion NOK. Essentially, the latter is a move to the eumetric yield curve (see Sect. 2). The chosen mesh size is with 206 mm for trawl and 238 mm for gillnets somewhat higher than *optimal harvesting* in order to compensate for the inability to reduce effort. In general, the scenario yields a biomass/harvest structure that is very similar to the scenario where both effort and mesh size were chosen (see Fig. 4d). It is therefore as capable as *optimal harvesting* to solve the problem of age truncation.

When only effort is a choice variable and *m* is fixed (see Fig. 4c), it becomes evident that the current regulation of 135 mm for trawl is maladapted: the optimization produces a cyclical fishing pattern. It is indeed remarkable that this pattern is optimal, in spite of our assumption of increasing marginal costs. This result is robust to a wide range of parameter specifications. It means that the value of the individual fish are growing with age at such a rate, that it is optimal to alternate harvesting with an effort of up to 16 million tonnage-days with no harvesting and stock recovery in order to increase the proportion of old and valuable fish in the harvest. As this is only imperfectly possible, there are too many old and too many young fish in the nets (Fig. 5). Although such an exploitation pattern is hardly a real option for this fishery, the simulation does show that too many age-classes are targeted indiscriminately at today's mesh size regulation.

4.3 Discussion

All in all, the age-structured analysis shows clearly that there is overfishing of the stock, but the problem is not so much that effort is employed excessively, but that too small fish are targeted. This result could be important in practice, when there is some rigidity in varying the effort levels of the fleets caused by technical or political reasons. For example, fishermen might reject to decrease their effort for fear of unemployment and financial loss. Increasing the minimum mesh size might hence prove a viable management alternative, potentially increasing the Net-Present-Value by 77 billion NOK over the next 50 years. Obviously, there will still be a time problem as the gains from the changes in the stock materialize only after a while. Nevertheless, the fleets make positive profits after 3 years, and after 4 more years they earn more than double of what they would have earned otherwise. At least in theory, a simple intertemporal subsidy/tax scheme could correct this problem.

As the cod biomass has varied between 0.74 and 2.36 million tons since 1980, one could argue that convergence to a high biomass of 6 million tones appears unrealistic. Our model assumes that mortality is density-dependent only in the recruitment phase while natural mortality among sub-adult and adult cod is assumed to be density-independent. The latter assumption can be expected to be increasingly wrong as biomass increases. However, cod biomass has been estimated to have reached around 5 million tons in 1936, when fishing pressure, in particular in Lofoten, was significant. Indeed, the North Eastern Arctic Cod stock has been commercially exploited for at least 1,000 years, it is difficult to estimate its carrying capacity in the absence of fishing. However, based on a meta-analysis using Bayesian methods, (Myers et al. 2001) estimated that the carrying capacity of this cod stock is 20 million tons. If this is so, we can expect competition among sub-adult and adult cod to be relatively low at 6 million tons, i.e., we make no grave error by assuming density-independent mortality.[11]

Due to the relative differences of the effective costs of employing one unit of effort for the different fleets, the use of the Norwegian trawler fleet was reduced more than the use of the Russian trawlers. However, due to the convexity of costs, the overall proportions remained fairly constant. Only in the cyclical fishing pattern of the *only E_t optimal* scenario was the use of the Lofoten fleet significantly reduced as its gear did not catch the fish effectively enough. When the trawlers can adapt their mesh size, they select for fish of 9 years and older. At that age, 91% of a year class have reached maturity and the Lofoten fleet loses its comparative advantage of targeting only mature fish. In general, neither fecundity nor cannibalism emerged as a prominent feature in the economic analysis. Targeting fish of age 9 and older avoids reproductive overfishing in addition to avoiding growth overfishing.[12]

4.4 Sensitivity Analysis

As the projections of alternative management scenarios rest on empirically estimated parameters, the sensitivity of the outcomes was tested. Raising / lowering the cost by 10% had no

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[11] The approach of Myers et al. (2001) can certainly be criticized, as it is basically based on extrapolation. However, it is worth noting that their estimate of the carrying capacity of the Scotian Shelf cod fits remarkably well with independent estimates of the same cod stock in the 1850s based on historical catch records (Rosenberg et al. 2005).

[12] We have made the conservative assumption that fecundity increases linearly, while it has been suggested for many fish species that one 8 kg female fish could be more productive than two females of 4 kg. To what extent the introduction of a non-linear fecundity pattern would make it worthwhile to refrain from harvesting cod until an even later age, would hinge on its exact specification. It was therefore deemed of little additional value to explicitly model this aspect.
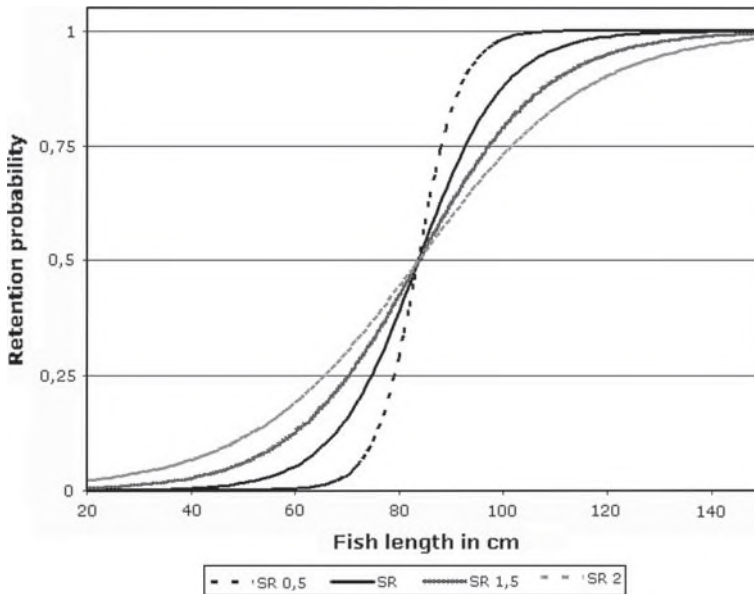
Fig. 6 Selectivity curves of trawl for different Selection Ranges (*SR*)

significant impact on the optimal exploitation pattern and it changed the obtainable NPV by less than 1%. This reaffirms 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). In fact, the value of the optimal mesh size appears to be independent of the cost structure. It did not change even for a linear specification of the cost function. In contrast, changing the discount rate to 3 and 7%, respectively had, as expected, a strong impact on the obtainable NPV. Intuitively, as impatience was increased, it was optimal to catch the fish somewhat earlier (mesh size of 196 mm) and the reverse was true for 3% discount rate (mesh size of 208 mm).

The relationship between a change in mesh size and the selection range (the steepness of the gear selectivity curve) were estimated for mesh sizes between 80 and 155 mm (Halliday et al. 1999) and it is not evident that these curves maintain their properties when the mesh size is enlarged to over 200 mm. The selection ranges were multiplied by a factor of 0.5, 1.5, and 2, respectively, resulting in considerably steeper or flatter curves (see Fig. 6). The results showed the pattern discussed in Sect. 2: For the steeper curve, the chosen mesh size was somewhat larger as one could tailor the gear better to target the 9-year-olds. As growth overfishing was avoided more effectively, effort was increased. Together this lead to an increase of profits by 6%. Contrarily, making the selectivity curves flatter lowers the efficiency of the gear. In the case where the selection range was multiplied by 1.5, the mesh size was reduced to 199 mm to make sure that all of the 9-year-olds were still exposed to the fishing mortality, while effort was reduced in order to lessen the unwanted fishing mortality placed on the younger fish. This reduced the NPV by 6%. Multiplying the selection range with a factor of 2 reduced the optimal mesh size to 194 mm and the NPV decreased by 12%.

When the overall efficiency of applying effort was changed (increasing/decreasing q) by 10%, the NPV changed by less than 3%. For a higher catchability, effort was decreased by 3.5% and the mesh size enlarged to 204 mm. Lowering q resulted in somewhat tighter nets

(200 mm instead of 202 mm) and slightly increased effort (by 4%). Finally, changing the prices by 10% lead to changes in economic profits of roughly 15%, but again, the changes in mesh size and effort level were smaller than 4%.

To sum up, the analysis corroborated that optimal exploitation of renewable resources is mainly characterized by the development of the stock value and the discount rate. The fact that the mesh size did not change by more than 8 mm given the quite substantive changes in parameters is indeed remarkable, in particular when compared to the 70 mm shift from today's level.

5 Conclusion

Our analysis highlights the necessity of age-structured modeling in applied fishery economics. Benefiting from an interdisciplinary approach, we could present a detailed multi-cohort, multi-gear bioeconomic example, modeled after the NEA cod fishery. It turns out that the economic gains from this resource could be doubled even by a change of mesh size regulations alone.

In spite of a history of 25 years of joint Russian-Norwegian fisheries management, the stock has clearly been overharvested during this period. Firstly, the authorities have tended to give quotas well beyond scientific advice. Secondly, actual harvest has been significantly higher than the quotas due to unreported and illegal fishing. Thirdly, the regulated mesh size is inefficiently small, wasting the larger part of the resource's potential. The planned reduction of the minimum mesh size to 130 mm is particularly worrisome in this respect. A driving factor of the ongoing overfishing might simply be the strategic interaction between the two nations exploiting this transboundary stock (Diekert et al. 2010). Future research should include these aspects into a bioeconomic analysis of the Barents Sea. Furthermore, one could fully exploit the possibilities of the biological model and ask how the underlying incentive structures change with regards to climatic fluctuations or fishery-induced evolution.

In general, the simulations reveal that mesh size is a choice variable which is at least as important as effort. Although this has not been an explicit objective, optimal age-specific harvesting pattern results in a biologically much healthier fish stock. The overall biomass would be increased, and the stock would consist of older and heavier individuals, making it more resilient to fluctuations in the environment. Maximizing economic gain and taking the age-structure into account could therefore lessen the risk of stock collapse, halten juvenescence, and stabilize variability in the fish stocks. These results could prove to be highly relevant for managers and policy makers.

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