Appreciating the value of age

An evaluation of efficiency gains from controlling gear selectivity under various scenarios

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Abstract: The central objective of fishery management is to ensure the sustainability and profitability of the resource base. The importance of the fish stock's age-structure is increasingly recognized in economics and ecology. Still, current policies predominately rely on the aggregate biomass. We calibrate a detailed model on the North-East Arctic cod fishery to assess the efficiency gains from controlling gear selectivity and explore them under a suite of different scenarios. In addition to providing an increased understanding of the determinants of age-structured harvesting, our study suggests that it is high time to move beyond traditional reference points and consider age-differentiated management tools.

Keywords: Bio-economics; age-structured model; gear selectivity; density-dependence; North-East Arctic cod

1 Introduction

Fisheries management predominantly relies on aggregate measures of stock biomass to set total allowable catch (TAC) targets. However, the importance of the fish stock's age-structure is increasingly recognized in economics and ecology. Sparing young and fast-growing fish from being harvested is an effective way of increasing the harvestable biomass which cannot be captured by aggregate models. It leads to higher catch per unit effort and hence increases the profitability of the fishery at the same time as it leads to a more abundant and robust resource base. In fact, it might be more important to avoid growth-overfishing than to focus on controlling the aggregate size of the spawning stock. The latter does not avoid growth-overfishing, but by containing growth-overfishing, the future viability of the fishery can be protected.

We calibrate a generic yet detailed model on the North-East Arctic (NEA) cod fishery to evaluate the effects of age-specific harvesting[1] under a broad variety of scenarios. This approach fills a gap between empirical studies that concentrate on specific aspects of specific fisheries on the one hand, and general analytical solutions that cannot speak about the magnitude of the involved trade-offs on the other hand. Two themes run through the paper. First, we aim at providing an "estimate of efficiency gains from [age-specific] optimal harvesting compared to currently applied biological reference points" as suggested by Tahvonen (2009a, p.297). Second, we seek to shed light on the sensitivity of optimal harvesting policies with respect to different modeling assumptions on the biological part. Previous empirical studies have generally assumed some specific form of the recruitment function without further discussion of its implications. Here we compare the effect of employing different recruitment functions. Moreover, the paper introduces density dependence in the growth function to the bio-economic literature.

In the model, the optimal first-age-at-capture is 9 years when recruitment is a random process. This leads to an annual profit of 11.3 billion Euro, which is roughly a 40% increase over the optimal harvesting pattern under today's selectivity pattern. When recruitment is increasing with the spawning stock biomass,

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[1] Generally speaking, fishing is a *size*-selective process (fish whose girth is smaller than the diameter of the mesh may escape through netting, while larger fish may not). However, size is closely related to age in most fish species. The latter is more convenient to use as it moves at the same speed as time (one year later, a given fish will be one year older). Moreover, data for fish stocks is routinely reported in age, not size.

the optimal first-age-at-capture is also 9. Annual profits and efficiency gains are higher since the manager can actively benefit from an increased spawning stock. When recruitment is decreasing with the size of the spawning stock after a certain point, the optimal first-age-at-capture is 6. Although the efficiency gains under this scenario are of limited scope due to the dynamic penalties from a high stock size, it is even more important to control gear selectivity in this case. It allows to separate the mature from the non-mature part of the stock. Concentrating harvest on the former keeps the size of the spawning stock in check, while allowing a sizable inflow of new cohorts every year. Additional considerations of density dependence and multi-species aspects also suggest to spare at least the fish that are younger than 6 years. At this age, an individual fish weighs 2.15 kg on average. In contrast, fish are caught from an age of 3 years on today, when they weigh 0.27 kg.

The reason for the current preoccupation with biological reference points is probably to avoid recruitment-overfishing. Recruitment-overfishing can be defined as a depletion of the reproductive part of the stock such that recruitment is impaired. Growth-overfishing can in turn be defined as depleting the young part of the stock before it has reached its full economic potential. The weight and value of a fish is generally increasing with age, but the overall numbers are decreasing with age due to natural mortality. As a consequence, there is generally one age at which the biovalue of a cohort attains a maximum.

Both forms of overfishing constitute negative inter-temporal externalities, which are lumped together in the classical bio-economic models. Indeed, growth- and recruitment-overfishing are confounded processes since recruitment, growth, and mortality cannot be separated. The onset of maturation is mostly conditional on having reached a certain weight, and also the fecundity and quality of offspring is believed to increase more than proportionally with weight in many species (Palumbi, 2004). Similarly, recruitment and mortality are often linked, be it because natural mortality is higher after spawning, or be it because fishing mortality is higher during spawning. It is nevertheless necessary to try to distinguish these processes for adequate management. It could be that by concentrating to avoid growth-overfishing, one effectively prevents recruitment-overfishing (Froese et al., 2008). In order to investigate this hypothesis, we contrast the optimal policies from a model where recruitment is exogenous, and hence has no influence on management decisions, to the optimal policies from various forms of endogenous recruitment functions.

The common perception is that growth-overfishing is the more wide-spread form of overfishing, whereas recruitment-overfishing has more disastrous consequences (Gulland, 1983): The latter directly impedes the future viability of fish stocks. However, also the damage from harvesting fish before they have grown to its optimal size could be high. This is particularly the case for species which grow significantly in weight and value with age. North East Arctic cod for example are currently targeted at an age where the fish would still grow in value with roughly 20% per year. Moreover, growth-overfishing is increasingly seen as a serious biological problem (Hsieh et al., 2006; Beamish et al., 2006; Ottersen, 2008), even – and perhaps especially – in those fisheries where the overall biomass is reasonably well managed. Due to the selective property of fishing gears, very few fish survive to grow old and large, implying a pronounced shift of the stock's age-composition. This effect is commonly referred to as "age truncation". Since old fish are better able to buffer adverse environmental fluctuations (Ottersen et al., 2006), growth-overfishing can lead to magnified fluctuations of abundance and decreased biological stability (Anderson et al., 2008). If harvesting has evolutionary consequences (Conover and Munch, 2002; Guttormsen et al., 2008; Jørgensen et al., 2009; Eikeset et al., 2010a), these changes may be irreversible (Stenseth and Rouyer, 2008).

The detrimental effect of harvesting fish that are too small was already a central issue in Petersen's report (1893), which was perhaps the first scientific treatment of fisheries management. Growth overfishing was clearly on the agenda during the rise of modern fishery science after the second World War (Allen, 1953; Beverton and Holt, 1957; Turvey, 1964), but the attention to it has subsequently dwindled. Even though age- and stage-differentiated modeling has recently gained traction in the resource economics literature, current state-of-the-art management strategy evaluations (Dankel et al., 2008; Kjærsgaard and Frost, 2008; Eikeset et al., 2010b,c; Brunel et al., 2010; Froese et al., 2010) do not explicitly consider changes in selectivity. Those yield-per-recruit analyses that do (Ulltang, 1987; Kvamme and Frøysa, 2004; Kvamme and Bogstad, 2007) neither include economic information nor seek to find the optimal harvesting pattern.

In fact, it almost seems ironic that aggregate bio-economic models often are rejected as being over-simplistic *de*scriptions of fisheries, while the *pre*scriptions of managers are predominantly given in terms of aggregate biomass. Surely, most management schemes do include some sort of gear regulation or minimum age/size limits, but these are mostly set *ad hoc* and far from being optimal. The preferred tool in most developed fisheries is the setting of total allowable catch (TAC) quotas (Froese et al., 2010). Based upon an estimate of the aggregated stock biomass, stock managers answer the question: "How much should be harvested?" Yet acknowledging the fact that fish stocks are not a uniform mass but consist of individual fish leads to a second question: "Which fish should be harvested?" It is important to answer this question correctly, not only due to potentially large efficiency gains, but also because gear regulations and minimum size limits are presumably easier to monitor and enforce. The latter aspect is especially relevant from the perspective of developing countries, where the use of elaborate stock surveys and advanced quota systems may be limited.

The main question of the paper is therefore: How much can be gained by correctly selecting which fish to harvest? To be able to make concrete statements, we calibrate a generic bio-economic model on a the North-East Arctic (NEA) cod fishery (section 2). By combining biology with economics, it is possible to exploit high quality data over a timespan which is rarely found in applied resource economics. Moreover, we introduce an estimated age-specific harvest function with this model, which – to the best of our knowledge – has not been done before. The simulation procedure is explained in section 3, and in section 4, we contrast:

(a) the maximum Net-Present-Value which is obtainable when only the harvested amount is controlled. In the model, this is achieved by choosing the level of fishing effort.

(b) the maximum Net-Present-Value which is obtainable when both amount and composition of the harvest is controlled. In the model, this is achieved by determining which age-classes should be spared from being harvested (i.e. by choosing the selectivity) and by choosing the appropriate effort level.

Recruitment in the baseline scenario is modeled as an i.i.d. draw from the set of past observations. This is motivated by the fact that recruitment is often driven by stochastic environmental fluctuations and no clear stock-recruitment relationship is discernible (Figure 1). In addition, it allows isolating the effect of growth-overfishing.

Section 5 deals with the question in how far the character of optimal policies changes when recruitment is not independent of the existing biomass. To over-state this case, we presume a deterministic recruitment function which is linearly increasing over the range of observed values and constant thereafter (dotted line in Figure 1). Under this scenario, the manager has complete control over next year's recruitment by keeping the spawning stock biomass at a given level.

Contrasting this scenario with the baseline case of random recruitment is conceptually different from analyzing the influence of uncertainty, on which an extensive literature exists. Under the baseline scenario, the manager has not only no knowledge, she has also no influence on future recruitment. However, the population is effectively subsidized by a (random) number of incoming fish, so that any concern about recruitment-overfishing is neutralized by construction.

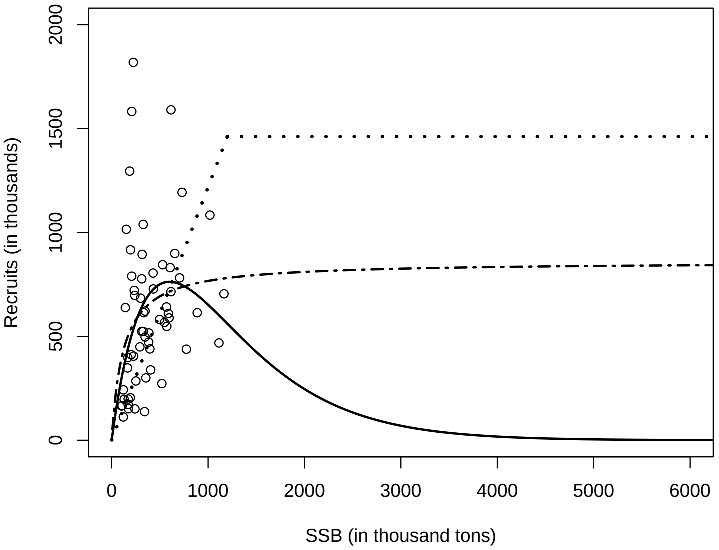

Figure 1: Spawning stock biomass and observed values of recruitment; model functions (linear = dotted, Beverton-Holt = dash-dotted, Ricker = solid)

Generally, projections of harvesting policies that maximize profits lead to vastly more abundant fish stocks. Surely aggregate stock growth is biologically regulated, implying decreasing returns to stock size. This is referred to as density dependence. Empirical bio-economic studies routinely include this effect by assuming that recruitment is either one of two classical functions (the "Beverton-Holt" or the "Ricker"-relationship). Although these two functions are often relatively similar over the range of existing observations, their asymptotic properties differ dramatically (see Figure 1). What are the implications of choosing one or the other recruitment function? Moreover, density dependent effects could also be at work at the level of individual growth. The potential importance of such an effect has been sketched by Botsford (1981), but its impact on economic harvesting has not been studied before. A first attempt is provided in section 6. The limitations of our work and avenues for further research are discussed in section 7. Section 8 concludes the paper.

Figure 2 visualizes the conceptual flow of our method. We compare the value obtained by selecting the best age-at-capture, with the value obtained under the current (non-optimal) selectivity pattern under a large set of scenarios. As each optimization of a model with 11-age-classes inevitably faces the curse of dimensionality, we do not – strictly speaking – solve an optimal control problem. Rather, we span a grid of rules and policies, repeatedly simulate the development of the model fishery for each specific scenario and identify the rule and policy which, on average, yields the highest Net-Present-Value.

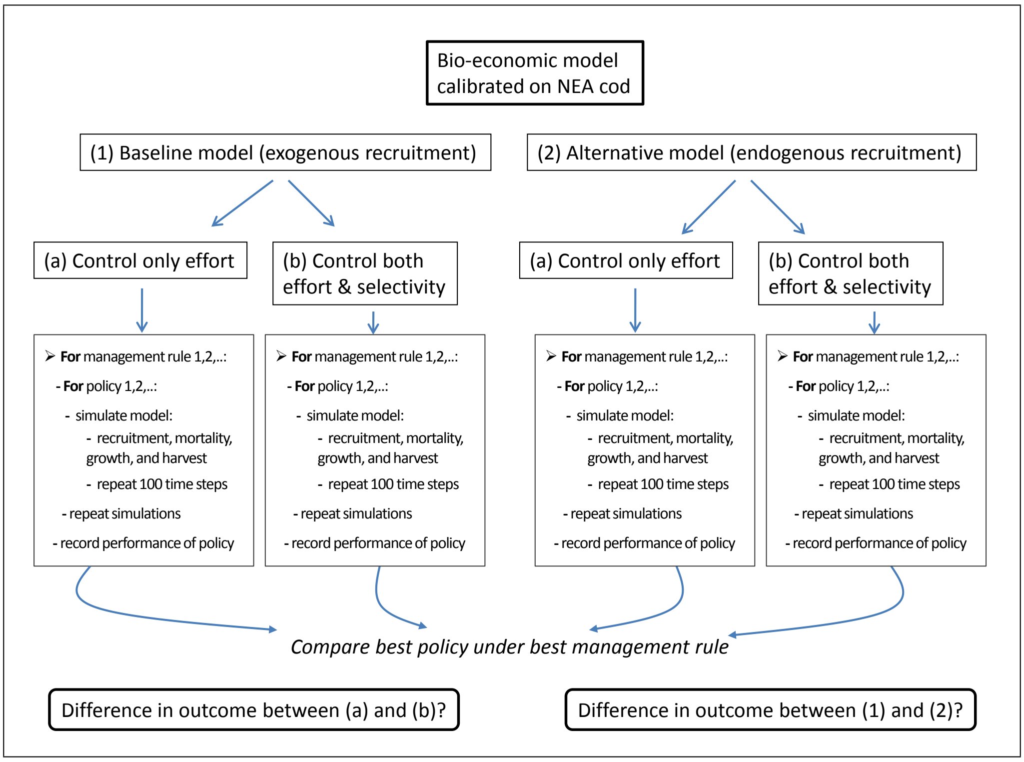

Figure 2: Sketch of method

2 Model calibration on the NEA-cod fishery

This section presents a general age-structured fishery model and our calibration on the North-East Arctic (NEA) cod stock. Details on the estimation of the economic parameters can be found in Appendix 9.1

The cod stock in the Barents Sea is the largest cod stock in the world, supporting one of the most valuable fisheries (FKD, 2008). Due to its importance, the fish stock and its fishery is thoroughly researched.[2] It is jointly managed by Russia and Norway. The total annual harvest is currently around 500 000 tons, taken both by a conventional coastal fleet (30%) and an ocean-going trawler fleet (70%) (ICES, 2010). We concentrate on the Norwegian trawler fleet for the calibration of the economic part of the model because of data availability. The model is calibrated on the period 1990-2005.

2.1 The biological part of the model

The sequence of events within one model year is recruitment, natural mortality, growth, and harvest.[3] To introduce some notation, let $n_{a,t}$ be the number of fish of age-class a at time t. As NEA cod are currently recruited to the fishery when they are three years old, the age-classes run from $a = 3$ to $A = 13+$ where the oldest age-classes collects all individuals of age 13 and above. Furthermore, denote the probability of surviving a given age-class by ϕ_a, the weight of a given age-class by w_a, and the proportion of mature individuals in a given age-class by mat_a.

The observed relationship between the number of recruits (in millions) and spawning stock biomass three years before (SSB, in thousand tonnes) is shown in Figure 1 (The data is from 1946 to 2009, see table 3.25 in ICES, 2010, p.209). There is a large variability in recruitment and no stock-recruitment relationship is directly discernible. For the baseline model, we therefore assume that recruitment is an exogenous random number R (equation 1), as in the classical analysis of Beverton and Holt (1957). We take R to be an iid. draw from all observed

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[2] A search of {cod AND 'North East Arctic' OR 'Barents Sea'} returned over 7500 hits on google scholar and over 5500 hits on ISI web of knowledge. For a general overview of the fishery see Nakken (1998). Recent bio-economic analyses include Diekert et al. (2010b,a); Eikeset et al. (2010b,c) and Richter et al. (2011).

[3] The order is of little consequence. Instantaneous harvesting is introduced mainly for convenience, which is common in economic but also in a number of ecological models (for a discussion see Tahvonen, 2009a, p.284). Zero mortality prior to spawning is also assumed in ICES (2010).

recruitment values between 1946 and 2009.

The development of an age-class from one year to the next is given by equation (2) and (3). The fish in age-class a at time t are those from the previous age-class that survive year $t-1$ (first term on the right-hand-side of equation 2), minus those that have been harvested (the second term on the right-hand-side of equation 2; since harvest h is specified in terms of biomass, it has to be divided by the age-specific weight to be given in terms of numbers). Equation (3) describes the cohort dynamics of the oldest age-class A. It collects all fish that newly enter this age-class from age-class $A-1$, as well as those fish that are already present in this age-class and have survived the previous year.

$$n_{3,t} = R \tag{1}$$

$$n_{a,t} = \phi_{a-1} n_{a-1,t-1} - \frac{h_{a-1,t-1}}{w_{a-1}} \qquad \text{for } a = 4, ..., A-1 \tag{2}$$

$$n_{A,t} = \phi_{A-1} n_{A-1,t-1} - \frac{h_{A-1,t-1}}{w_{A-1}} + \phi_A n_{A,t-1} - \frac{h_{A,t-1}}{w_A} \tag{3}$$

All age-classes but the oldest face the same annual risk of dying from natural causes, so that the survival probability is $\phi_a = 0.8$ for $a = 3, ..., A-1$.[4] We set the survival probability of the oldest age-class to $\phi_A = 0.5$ to account for senescence and to prevent it from accumulating unreasonable amounts of biomass. Parameters for weight-at-age (w_a) and the proportion of mature fish (mat_a) are taken to be the average values from 1990-2005,[5] so that the biological and economic model are calibrated on the same time period (see Table 1).

Table 1: Biological Parameters

Age a	3	4	5	6	7	8	9	10	11	12	13+
w_a (in kg)	0.27	0.6	1.29	2.15	3.29	4.76	6.71	9.25	10.85	12.73	14.31
mat_a	0.001	0.008	0.07	0.31	0.64	0.85	0.96	0.99	1	1	1

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[4] ICES uses a natural mortality of 0.2 in its stock assessment and Jørgensen and Fiksen (2006) use a value of 0.25 in their detailed model of cod life-history. Recent state-space modeling (Aanes et al., 2007) show that there is large uncertainty around the point estimate, but that natural mortality fluctuates much more through time than over age. Using advanced statistical methods, Brinch et al. (2011) confirm that a guess of 0.2 is indeed not far off the mark.

[5] The data is from table 3.11, pp.179, and 3.12, pp.182, in ICES (2010) respectively.

Implications of the biological model

Table 2 shows the relative growth (in weight) of a cohort over age. The biomass of a cohort reaches its maximum when its growth rate equals the natural mortality rate (see e.g. Clark, 1990, p.277). Here $1-\phi = 0.2$, so that the growth in weight of the individual fish outweighs their decline in numbers due to natural mortality when they are younger than 10 years and vice versa when they are older than ten years. Hence, abstracting from all economic considerations of cost, prices, and discounting, it would be optimal to harvest fish of age 10.

Table 2: Growth in weight

Δ_a	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
$\frac{w_a - w_{a-1}}{w_a}$	0.55	0.53	0.4	0.35	0.31	0.29	0.27	0.15	0.15	0.11

Figure 3 gives a graphical illustration of Table 2 by plotting a cohort's biomass relative to its biomass at recruitment. The contrast between the development under no fishing (open circles) and the average exploitation pressure between 1990-2005 (filled circles) is obvious, but Figure 3 also points to the magnitude of changes that could be implicated by moving from current management to optimal management.

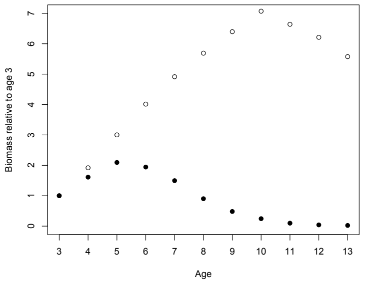

Figure 3: Cohort biomass for no- and current fishing (open and filled circles)

2.2 The economic part of the model

The cod fishery of the Barents Sea is in fact a multispecies fishery. After cod, saithe and haddock are the most important species in terms of harvested volume. The boats can therefore be characterized as joint-input, multi-output firms, where a common mix of inputs is used to produce several products (Squires, 1987;

Jensen, 2007). We assume that the production of cod harvest can be separately regulated without affecting other production processes (output-separability). While a full biological and economic multi-species model is beyond the scope of this study, we do discuss the implication of this assumption in section 7.

Harvest function

Harvest h is related to the mix of production inputs, subsumed as effort e, and the existing stock biomass, denoted by x, according to some unknown process. It is common to model it by using the Cobb-Douglas function $h = qe^{\alpha}x^{\beta}$. The parameter β is the stock-output elasticity. It captures the spatial behavior of the fish stock and tells how much harvest increases when the stock increases by one unit.[6] The value of α tells how much harvest increases when effort increases by one unit. Lastly, q is the "catchability coefficient", which basically functions as a scaling coefficient capturing how a given stock biomass translates into harvestable biomass.

However, this interpretation is problematic as the "catchability" depends both on the targeting behavior of the fisherman and on the spatial availability of the fish. Moreover, in the age-specific case, "catchability" is confounded with selectivity: A fish may have not been caught because the fisherman did not find it, because the fisherman found it but the fish avoided the gear, or because the fish had contact with the gear but was not retained (Millar and Fryer, 1999).

One way of explicitly modeling the choice which age-classes are harvested is to pre-multiply the harvest function with the probability of being retained in the gear, conditional for a given age (selection curves are published to a large extent, see Millar and Fryer, 1999). This approach has been used by Diekert et al. (2010a,b). While it allows to isolate the selectivity pattern of the gear, it may obscure the fact that it cannot separate the targeting behavior of the fisherman from the spatial behavior of the fish. What is more worrisome is that the aggregate stock elasticity is estimated on the current selectivity pattern, and it is not clear whether it remains its property when significantly fewer age-classes

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[6] If the fish stock follows an ideal free distribution ($\beta = 1$), the density of fish declines at the same rate as the stock gets depleted. Often it is argued that this is an adequate description for demersal species such as cod (Clark, 1990). However, empirical studies have shown that this does not hold true for the NEA cod. Richter et al. (2011) for example find that β ranges between 0.22 for longliners and 0.58 for trawlers. Eide et al. (2003), using daily biomass estimates for the period 1971-1985, find a value of $\beta = 0.42$ and Hannesson (1983), concentrating on the coastal fishery between 1950-78, finds values between 0.74 and 0.90.

are selected.

Another way of explicitly modeling the choice which age-classes are harvested is to estimate age-class specific parameters β_a and to include only these age-classes in the harvest that are older than the chosen first-age-at-capture. This approach is taken here. It is made possible by the available panel of Norwegian Trawlers (for details on data and regressions, see Appendix 9.1). The interpretation is that effort produces an amount of water which is screened for cod, irrespective of age. The potentially harvestable stock is then determined by the selectivity parameter $s \in [3, A]$ where all age-classes at least as old as s are targeted. The status quo is that all age-classes are targeted ($s = 3$). Changing the selectivity pattern (choosing $s > 3$) means that all age-classes younger than s are spared from being harvested. This can be thought of as a technical modification of the gear so that a fish, even if it were to have contact with the gear, would not be retained.

On the one hand, this means that it is not possible to isolate the technical retention pattern of the gear. On the other hand, it means that the translation of stock biomass to harvestable biomass for a given age-class does not depend on the other age-classes which are selected. Moreover, this modeling approach greatly enhances the transparency of the model, although knife-edge selectivity is of course a simplification.

The harvest equation is then given by (4), where we use a vector of indicator variables i which take the value of zero for $a < s$ and the value of one for $a \geq s$. The calibrated values for β_a are given in Table 3.

$$h = \sum_{a=s}^{A} h_a = \begin{bmatrix} i_3 & \dots & i_A \end{bmatrix} q e^{\alpha} \begin{bmatrix} x^{\beta_3} \\ \vdots \\ x^{\beta_A} \end{bmatrix} \quad \text{where} \quad \begin{cases} i_a = 0 & \text{for} \quad a < s \\ i_a = 1 & \text{for} \quad a \geq s \end{cases} \tag{4}$$

Table 3: Age specific stock elasticities

Age	3	4	5	6	7	8	9	10	11	12	13+
β_a	0.73	0.88	0.93	0.95	0.96	0.96	0.95	0.94	0.92	0.92	0.93

Profits, costs, and prices

The revenue from fishing is the age-class specific harvest times the vector of prices-at-age[7] (see Table 4).

Table 4: Price at age

Age	3	4	5	6	7	8	9	10	11	12	13+
p_a (Euro/kg)	1.36	1.36	1.79	1.79	1.97	1.97	2.28	2.28	2.28	2.28	2.28

Costs are caused by effort and found to be linear with $c = 7.82$ Euro (for details on the regression see Appendix 9.1). Hence, profits can be written as equation (5):

$$\pi = ph(e_t, s_t, x_t) - ce_t \tag{5}$$

Equation (6) describes the Net-Present-Value (NPV) of the fishery for a given sequence of effort and stock values. The NPV is the sum over all annual profits, discounted by a factor δ. We set δ to 0.95, implying a discount rate of 5%. Later, we investigate the sensitivity of the results for a range of discount rates between 2% and 10%. Maximizing (6) is the objective of the manager.

$$NPV = \sum_{t=0}^{T} \delta^t \pi(e_t, s_t, x_t) \tag{6}$$

Implications of the economic model

Similar to the biological model above, let us take a step back and look at the implications of the economic model. Table 5 shows the relative growth (in value) of a cohort over age. The only difference to Table 2 is the non-continuity introduced by the increase in price per kg that occur at age 5, 7, and 9. Again, the cohort reaches its highest biovalue when its growth rate equals natural mortal-

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[7] In the most recent study of the NEA cod fishery, Richter et al. (2011) elaborately estimate how prices depend on the quantity landed, using aggregate data. We are interested in the age-specific prices, not the least because larger fish get a higher price per kg. Prices-at-age (or, more precisely, prices-at-weight) are obtainable from the Norwegian fishermen's sales organization. However, the issue is plagued with problems of identification (Gates, 1974). Moreover, 90% of the cod products are exported to the larger world market for whitefish, and the first hand sales are furthermore regulated by minimum prices (Asche et al., 2001). We therefore take the average values from 1997-2004 as a ballpark estimate of the vector of dock prices.

ity, so that, without considering discounting and costs, it would be optimal to harvest fish of age 10.

Table 5: Growth in value

Δ_a	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13
$\frac{v_a - v_{a-1}}{v_a}$	0.55	0.65	0.4	0.41	0.31	0.39	0.27	0.15	0.15	0.11

A higher rate of discount shifts the optimal first-age-at-capture forward. Parallel to the decision when to cut a tree (Samuelson, 1976), we would liquidate a single cohort of fish when its growth in value equals natural mortality and the rate of discount. For the present parameter values, this implies that we would spare fish younger than 9 years for discount rates of up to 7% and we would spare fish younger than 8 years for discount rates of up to 19%.

However, the problem of the manager is not to harvest a single cohort of fish, but to find the harvesting pattern which maximizes the Net-Present-Value. Surely, the answer will be informed by the underlying parameter values of cohort growth, prices, and discounting, but it will also be influenced by the formulation of the harvest technology and cost function.

Since the harvest function is concave in each age-class, it introduces an incentive to keep an equilibrated biomass rather than concentrating harvest on one age-class. Albeit, with values of β_a mainly between 0.92 and 0.96 this effect is likely to be small. More important is the fact that costs are associated only with effort, regardless of how many age-classes are selected. As effort and selectivity are substitutes in the harvesting process, there is an economics of scale argument to target more age-classes. When costs of effort are very high, this economics of scale argument will be important and it will be optimal to target many age-classes with low effort. When costs of effort are low, the economics of scale argument will be outweighed by the opportunity costs of having a higher and more valuable biomass by sparing the fish for longer. It will be optimal to choose a high effort but to target only few old age-classes.

3 Description of simulation procedure

Having described the model of the NEA-cod fishery in some detail, we now turn to the numerical procedure: We use the program “R” (R Development Core Team, 2010) to simulate the development of the fishery and record its performance (the code is documented in Appendix 9.2). As mentioned in the introduction, this is strictly speaking not the maximization of an objective function over a general domain. The dimensionality of the state-space prohibits the use of dynamic programming. Instead, we explore a large set of (feedback) rules and policies from which we pick that combination of control variables which, on average, yields the highest NPV.[8]

By "rule" we mean a general way of determining the exploitation pattern, which subsumes a number of different policies. A "policy" is then the specific embodiment of a rule. For example, the rule could be to harvest a share of the existing biomass. A corresponding policy could then be to harvest 20% of the existing biomass. For each policy, the simulations of the model fishery are replicated 500 times so that the average NPV will not be influenced by the random events. The grid of policies that are evaluated is consecutively narrowed until the average NPVs from the three best policies differ by less than 1 standard deviation.

In the case where selectivity is a control variable, the rules for choosing it are:

A.) fixed selectivity: Set a fixed selectivity pattern, $s_t = s \in [3, 4, ..., A]$.

B.) variable selectivity: Select that age-class which is at distance θ from the age-class of maximum biomass, $s_t = a_{max,t} + \theta$.

Rule A.) is a rigid exploration of the effect of selecting a given age-class. Rule B.) installs a feedback between state and control and requires some elaboration: Since for a given recruitment, the number of fish is subsequently declining with age, but the weight per individual is increasing, there will be one age-class whose biomass is largest (call it a_{max}). As the number of incoming fish will fluctuate under random recruitment, the age-class of maximum biomass will change over time. Formally, rule B.) can be expressed as $s_t = a_{max,t} + \theta$, where $a_{max,t}$ and

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[8] At large, the optimal solution to dynamic fishing problems with aggregated biomass is to steer the stock from its initial state to the optimal steady state. However, also cyclical solutions ("pulse fishing") are discussed in the literature (Hannesson (1975), see Diekert et al. (2010b) for a demonstration of this mechanism in NEA cod). Our approach cannot capture these. This is in fact in our intention, since pulse fishing is often a response to inadequate gear selectivity, while we want to contrast the maximum NPV that can be obtained by changing gear selectivity with the suboptimal result when growth-overfishing cannot be contained. Tahvonen (2009a, p.296) proves that under some qualifications, the optimal solution converges to the steady state equilibrium also in the case of several age-classes when gear selectivity is appropriate.

consequently s_t may vary with time, but θ is constant. For example, when $\theta = 1$ we have that the age-class which is one year older than a_{max} is the first age-class to enter the harvest. θ can take values between -10 and 10 provided that $s_t \in [3, A]$.

The control variable effort is chosen according to one of the following four rules:

1.) HCR: At spawning stock levels above 460 thousand tonnes (this is called the B_{pa} reference point), apply a given value of fishing mortality F. At stock levels below B_{pa}, fishing mortality declines linearly to zero.

2.) fixed e: Employ a fixed level of effort.

3.) feedback e: Set effort proportional to total stock biomass.

4.) escapement: For a given target level of overall biomass (escapement), do not harvest when the biomass is below the escapement level. When the stock biomass is above the target level, skim the surplus.

Rule 1.) is close to the harvest control rule (HCR) agreed upon by the Joint Russian-Norwegian commission (ICES, 2010). Currently the fishing mortality is set at $F = 0.4$. Each simulated policy will be one value of F between 0.05 and 1.[9]

Rule 2.) is a rigid exploration of the parameter space. Effort per boat takes values between the minimum effort observed in the sample ($e_{min} = 1500$) and twice the maximum effort in the sample ($e_{max} = 500000$).

Rule 3.) yields feedback policies, where effort is proportional to the aggregate biomass of the fish stock. The factor of proportionality takes values between 0.005% and 50%.

Rule 4.) is known as "optimal escapement" rule (Reed, 1979) which characterizes the solution to the linear optimal control problem with an aggregate biomass model. It will most likely not be optimal in the current setting: First, the harvest function is not linear. Second, the target escapement level is given in terms of aggregate biomass, but the stock is age-structured, so that the optimal approach

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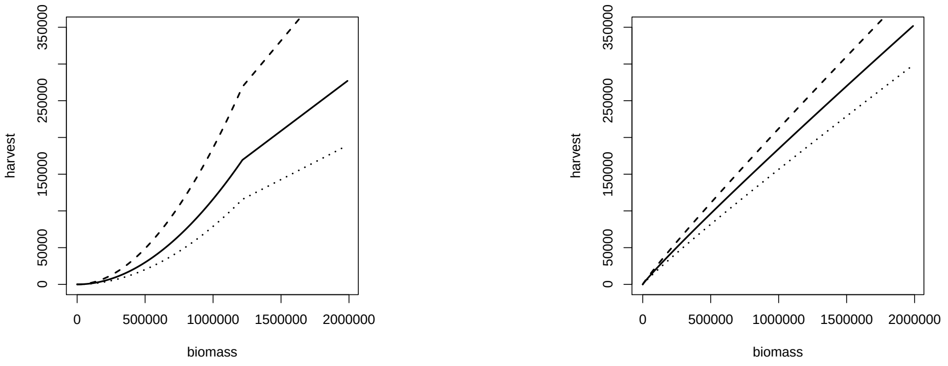
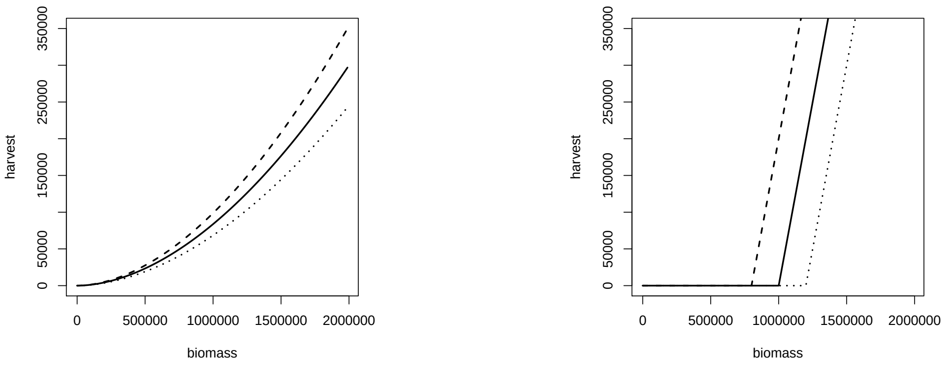
[9] Additionally, the current HCR specifies that F should not drop beneath a level of 0.3 at SSB levels above B_{pa} and the calculated total quota should vary by no more than 10% from year to year. We dispense of these additional qualifiers, which are mainly politically motivated. The effect of choosing different HCRs for the NEA cod fishery for the current selectivity pattern has been extensively studied by Eikeset et al. (2010b).

path will depend on the distribution of biomass over the different age-classes and may involve several periods of over- and undershooting (Tahvonen, 2009b). Still it is interesting to evaluate the performance of such a rule, especially since it has a strong influence on practical policies (Froese et al., 2010; the HCR is in effect similar to an escapement rule with given target level). The escapement policies range from 400 000 tons to 14 million tons.

Figure 4 gives a graphical illustration of these four rules. It shows how, at the current selectivity, each rule maps a given aggregate biomass into aggregate harvest.[10] The dotted/solid/dashed line is an example of a low/intermediate/high value of the respective control parameter.



1.) HCR 2.) fixed e



3.) feedback e 4.) escapement

Figure 4: Illustration of effort control rules

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[10] The harvest function $h = qe^{\alpha}x^{\beta}$ is concave in effort and biomass ($\alpha, \beta < 1$) but $\alpha + \beta > 1$, so that the mapping from biomass to harvest is slightly concave when effort takes a fixed value and convex when effort is proportional to biomass.

4 Results for the baseline model

This section presents the results from the baseline model, against which the other simulations will be compared. By shutting off a possible feedback from the standing stock to recruitment, and contrasting the maximum obtainable Net-Present-Value when only effort e is chosen and selectivity is set constant at its current level ($s = 3$), to the maximum obtainable NPV when both effort e and selectivity s are choice variables, the baseline model gives the clearest account of the benefits from avoiding growth-overfishing. Furthermore, the section discusses the relative performance of the different harvesting rules. An overview of the results is given in Table 6. Finally, we analyze the sensitivity of our findings to changes to the estimated economic parameters.

4.1 Efficiency gains from controlling gear selectivity

The efficiency gains from controlling selectivity are indeed large. Overall rule 3, according to which effort was set proportional to aggregate biomass, performs best. It yields a NPV of 32.4 billion Euro when selectivity is set to $s = 9$ and a NPV of 22.7 billion Euro when selectivity is constrained to $s = 3$. This implies a gain of nearly 10 billion Euro over a 100 year horizon. Throughout, avoiding growth overfishing leads to a 30-40% increase in obtainable NPV. Keep in mind that I do not contrast optimal exploitation paths with business-as-usual projections. Rather, the reported outcome of the scenario “only e” is the maximum obtainable NPV under current selectivity. For comparison, a projection of today’s policy target (i.e. a simulation of rule 1 with a fishing mortality of $F = 0.4$) yields a NPV of 19.7 billion Euro.

Figure 5 plots the maximum NPV which is obtainable at each first-age-at-capture $s = 3, 4, ..., 13$. As already suggested by the inspection of the growth increments in weight and value, the obtainable NPV is increasing until a first-age-at-capture of 9 years. Deferring the first-age-at-capture from 3 to 4 years yields almost no gains, but thereafter the relative gains from deferring the onset of harvesting by another year increase almost linearly.

Figure 6 shows the development of biomass and harvest for the optimal selectivity ($s = 9$, solid line) and the current selectivity ($s = 3$, dotted line). The two panels on the left plot the average paths. The two panels on the right side show the path of one specific simulation so that the involved variability becomes

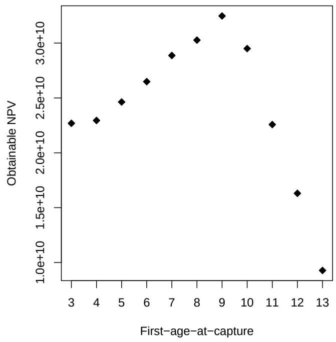

Figure 5: Obtainable NPV for given first-age-at-capture, baseline model (random recruitment)

visible.

The average aggregate biomass under the best policy is 5.7 million tons (with fluctuations of up to 8.2 million tons). Similarly, the biomass under the current selectivity is around 5.7 million tons. The average aggregate harvest under the best policy is roughly 1 million tons (with fluctuations up to 2.2 million tons). In contrast, the average aggregate harvest under the current selectivity regime is only about 500 thousand tons. For comparison, the average biomass over the last twenty years was 1.5 million tons (with a maximum of 2.4 million tons in 1993). The average harvest was 500 thousand tons (with a maximum of 762 thousand tons in 1997). The highest biomass of the NEA cod stock since 1932 was 4.2 million tons (in 1946).

When selectivity is fixed to its current level, the high biomass values that go along with maximizing profits come solely from restraining effort. As already Beverton and Holt (1957) argue, the same yield can be obtained by increasing effort and postponing the first-age-at-capture. Adequately managing gear selectivity implies that the fish stock will be closer to pristine conditions than it has been. It also leads to drastic changes underneath the values of aggregated biomass. Figure 7 shows the cohort biomass development under current conditions (filled circles) and under the optimal harvesting regime (open squares). This is the reason why the average total biomass is very similar when $s = 3$ or $s = 9$, but under the optimal selectivity scenario, almost twice as much is harvested.

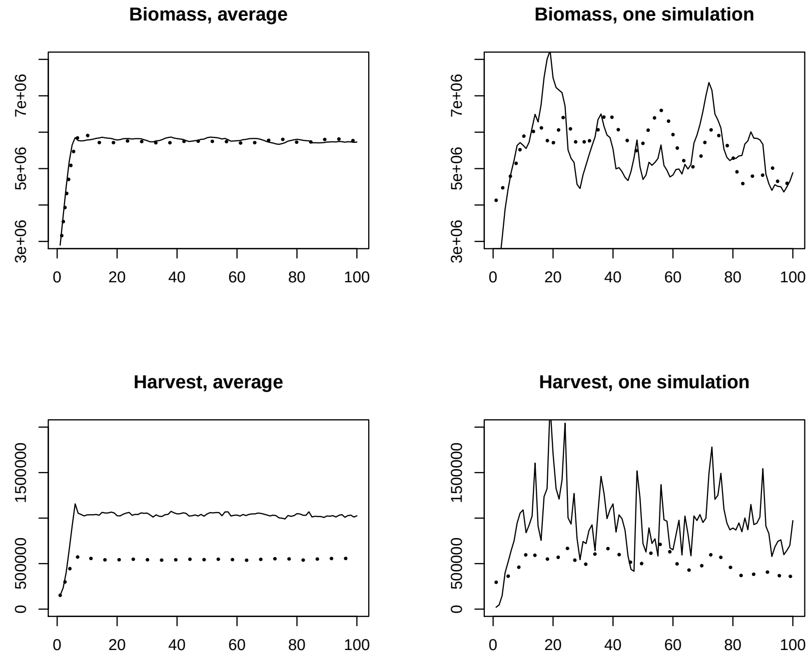

Figure 6: Biomass and harvest under current selectivity (dotted lines) and optimal selectivity (solid lines)

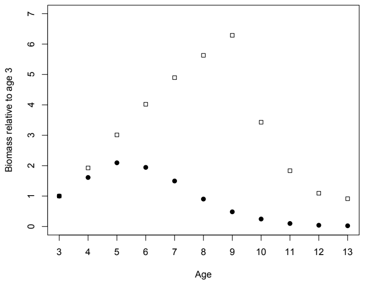

Figure 7: Cohort biomass at current selectivity (filled circles) and optimal selectivity (open squares)

4.2 Relative performance of different harvesting rules

Overall, the best policies under the different rules lead to very similar outcomes. This suggests that there is indeed an optimal steady state in the underlying dynamical system which the best performing policies aim at. In particular, the best selectivity is – except in one case – the same.

Table 6 shows for rule 1.) to 4.) the policy which maximizes the NPV (given in billion Euro) for the respective scenario. The values of the resulting average effort, biomass, and harvest are given in units of thousands.

Table 6: Overview of results; base-line model

Rule	**scenario**	**policy**	**effort**	**select.**	**biomass**	**harvest**	**NPV**
1.) HCR	only e	$F = 0.22$	122	3	3 600	672	22.6
	e and s	$F = 0.2$	221	8	5 321	907	28.1
2.) fixed e	only e	$e = 122$	122	3	4 450	633	22.7
	e and s	$e = 284$	284	9	5 391	1 043	31.9
3.) feedback e	only e	$e = 3.34\%x$	119	3	5 673	537	22.7
	e and s	$e = 5.50\%x$	311	9	5 656	1 012	32.4
4.) escapement	only e	$\bar{x} = 400000$	83	3	4 585	612	21.1
	e and s	$\bar{x} = 500000$	308	9	5 928	944	29.3

The conjecture that a constant escapement policy (rule 4) would not perform best is confirmed. Since the age-composition is constantly changing, an overall biomass target does not give a good fit to the actual harvest. The qualitatively similar HCR (rule 1) leads to lower outcomes as compared to both the rules where effort is constant over time (rule 2) and where effort is proportional to stock size (rule 3). For the current selectivity, optimizing only effort (implying $F = 0.2$) leads to relatively small economic gains compared to the current policy target of $F = 0.4$, supporting the findings of Eikeset et al. (2010b). The NPV increases by 2.9 billion Euro from 19.7 to 22.6 billion Euro, and also average harvest increases only slightly (672 instead of 667 hundred thousand tons). However, there is a more pronounced increase of average biomass (3.6 instead of 2.3 million tons).

The results under the variable selectivity rule are generally below the obtainable NPV from constant selectivity pattern and we therefore do not report them in further detail. For completeness, we note that the maximum obtainable NPV was 25.9 billion Euro, again from rule 3.). It results from setting $\theta = 0$ (so that in fact the age-class of maximum biomass is targeted), which yields an average first-age-at-capture of roughly 7 years. Not surprisingly, an adaptive selectivity pattern leads to less variable harvest.

Also the current selectivity pattern leads to a less variable harvest (compare the lower right panel in Figure 6). The reason is that with an earlier age-at-first-capture, more age-classes are subjected to harvesting pressure. The cohort specific variability in abundance, which emanates from the random recruitment is therefore smoothed out. In contrast, when the cohorts are subjected to harvesting pressure at a late age, the variability stemming from the random recruitment is exacerbated by the relative growth in biomass.[11] The lower variability is of course achieved at the cost of lower profits and lower effort, which may have repercussions for employment. These additional aspects may very well be important for a real-world manager. However, we set the objective to be the maximization of the fisheries value. Additional concerns should not be added *ad hoc*, but rather modeled explicitly, e.g. in form of a viability analysis (Lara and Martinet, 2009).

Furthermore, we experiment with defining rules in terms of harvest instead of effort. These yield inferior results, confirming the study Hannesson and Steinshamn (1991). The reason is that the cost of harvesting a fixed amount become excessively high in times of low stock biomass.

Finally, by setting annual effort proportional to the overall stock biomass in a given year, we implicitly assume that the entire stock is observable. In reality, the main input for stock assessment comes from catch data (although there are independent research surveys). We run additional simulations where effort cannot be conditioned on the entire stock biomass, but only on the biomass from those age-classes that are actually selected. The results do not change.

Although the simulations for the remaining part of the paper are largely conducted for the whole suite of different rules, from now on we focus on the feedback effort rule (rule 3). Throughout, this rule performs best and the differences among the other rules are of minor interest.

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[11] This is not an optical effect: The coefficient of variation for the harvest with constrained selectivity is 0.19 with a 95% C.I. of [0.17–0.23], whereas the coefficient of variation for the optimal selectivity is 0.38 [0.33–0.45]. For biomass it is 0.10 [0.9–0.11] with current selectivity and 0.18 [0.16–0.21] when $s = 9$.

4.3 Sensitivity Analysis

In order to analyze the sensitivity of our results on changes in the empirically estimated parameters, we run additional simulations of the best performing rule. Table 7 gives an overview when both effort and selectivity are control variables according to rule 3. It shows that the model results, in particular the optimal first-age-at-capture, are robust to reasonable changes in parameter values.

Table 7: Overview of results from sensitivity analysis

Parameter	**change**	**policy**	**effort**	**select.**	**biomass**	**harvest**	**NPV**
cost	+ 10%	$e = 5.50\%x$	311	9	5 660	1 013	31.3
	- 10%	$e = 5.68\%x$	318	9	5 613	1 017	33.1
prices	$p\cdot 1.5$	$e = 6.46\%x$	351	9	5 428	1 033	42.8
	$p\cdot 0.75$	$e = 4.47\%x$	266	9	5 947	975	21.8
stock elasticity	$\beta_a + 0.03$	$e = 4.79\%x$	250	9	5 228	1 045	35.9
	$\beta_a - 0.03$	$e = 6.93\%x$	414	9	5 982	978	27.5
discount	$\delta = 0.91$	$e = 6.87\%x$	367	9	5 349	1 039	14.2
	$\delta = 0.98$	$e = 6.07\%x$	336	9	5 534	1 031	75,7

First, we change the cost parameter. Making each unit of effort 10% more expensive, leads to a decrease of NPV of 3.5% and making each unit of effort 10% cheaper, lead to an increase in NPV of 2% on average. The resulting effort, biomass, and harvest are virtually unchanged and the best selectivity pattern is the same. The insensitivity of the simulation results to changes in the cost function are well in line with earlier results.

In principle, changing the slope of the value growth curve could lead to a different optimal first-age-at-capture. To test the sensitivity of the results with respect to this aspect, we multiply the vector of age-specific prices by 1.5. This increases the NPV to 42.8 billion Euro but does not yield a different first-age-at-capture. When the vector of age-specific prices is multiplied by 0.75, the NPV drops to 21.8 billion Euro, but again the first-age-at-capture does not change.

Another source of uncertainty is the estimation of the stock elasticities in the harvest function. We therefore increase and decrease all age-specific elasticity parameters by 0.03. Again, the optimal selectivity does not change. As it is intuitive, it is optimal to use less effort when the stock elasticity increases and use more effort in the opposite case. The changes also have an impact on the obtainable NPV: with higher stock elasticity parameters, the NPV decreases by roughly 15%; with lower stock elasticity parameters, the NPV increases by roughly 15%. Nonetheless, the relative efficiency gains are of similar magnitude as before.

Furthermore, we change the discount rate. It is to be expected that this has a strong impact on the obtainable NPV: At a 2% discount rate, one Euro in hundred years is worth 13 cents today, while at a 10% discount rate, one Euro has a present value of 0.007 cents. In spite of having this large impact on the NPV, ranging the discount rate between 2% and 10% does not result in different policies, which is not surprising given the strong growth in weight and value of NEA cod (refer to Table 1 and 4).

5 Model with endogenous recruitment

So far, the number of new fish recruited to the fishery has been completely independent of the size of the spawning stock. In other words, the fishery is effectively subsidized by a (random) positive inflow of new fish. However, the main motivation for today's preoccupation with aggregate reference points is to ensure sufficient recruitment in the future by protecting the overall size of the spawning stock. The following section therefore asks how the introduction of a link between the standing stock and recruitment influences the simulation outcomes. Since this allows to control recruitment by controlling the overall size of the spawning stock, it is not clear whether it will still be as valuable to change the current selectivity pattern. On the other hand, recruitment can also be guaranteed by installing a sizable age-refuge so that fish start reproducing before they are subject to harvesting pressure.

In order to study these questions, we contrast the baseline model, where recruitment is exogenous, to a model where recruitment is endogenous. That is, recruitment will now be determined by the spawning stock biomass (SSB), which is defined as the aggregate biomass of all mature individuals: $SSB = \sum_{a=3}^{A} w_a n_a mat_a$. If the difference between these two models in terms of optimal policies is small but the relative efficiency gains from changing gear selectivity are still large, then this indicates that there is little additional value in basing management decisions on aggregate biological reference points.

5.1 Recruitment as a linear deterministic function

The case of endogenous recruitment is deliberately overstated by assuming that recruitment is a deterministic function. The function is illustrated by the dotted line in Figure 1 in the introduction. It is proportional to SSB over the domain of observed values and constant at its highest level thereafter (which is in fact in line with a Leslie-matrix model). Hence, we fit the data to a linear regression forced to pass through the origin (Table 8). In the model, equation (1) is replaced by equation (7).

Table 8: Regression results for deterministic recruitment function

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
SSB	1.2182	0.1213	10.04	1.83e-14

$$n_{3,t} = \begin{cases} 1.2182 \cdot SSB & \text{if} \quad SSB \leq 1.2 \text{ million tons} \\ 1.46 \text{ millions} & \text{if} \quad SSB > 1.2 \text{ million tons} \end{cases} \tag{7}$$

The main result from the simulations with deterministic recruitment is given in Table 9. We report only the results for rule 3 as it continues to perform best and the other rules are qualitatively similar. The only difference is that, in contrast to the baseline model, the escapement rule performs relatively better. The reason is that in the deterministic case, the stock reaches a stable age structure and the aggregate biomass is then an informative measure. For all rules, it is best to target fish from age 9 on. Introducing a link between stock and recruitment does hence not induce a different optimal first-age-at-capture. Throughout, the relative gain from choosing gear selectivity are larger than in the baseline model and amount to a gain of 40-55% in NPV.

Table 9: Results from model with deterministic linear recruitment function

Rule	**scenario**	**policy**	**effort**	**select.**	**biomass**	**harvest**	**NPV**
3.) feedback e	only e	$e = 1.72\%x$	135	3	9 900	1 498	50.4
	e and s	$e = 3.52\%x$	303	9	12 067	2 445	77.6

Whether or not recruitment is deterministic has a large influence on the size of the standing biomass, harvest, and obtainable profits. Not only are these much higher under deterministic recruitment, it is also relatively more important to select the right age-class. There are two reasons for that. First, in the baseline model, the fishery is supplied with roughly 600 thousand recruits per year, while the deterministic fishery receives an annual inflow of 1.4 million recruits in equilibrium. Hence, the standing stocks in the two scenarios reach two very different levels. In the deterministic scenario, overall biomass and harvest is more than twice as much as in the random scenario. Second, as mentioned in the introduction, growth and maturity are closely linked processes. In general, fish mature when they have reached a given size, which is the ultimate reason why an adequate size selection effectively means a protection of the spawning stock. In the random scenario, the manager cannot benefit at all from this, since recruitment is independent of the spawning stock by construction.

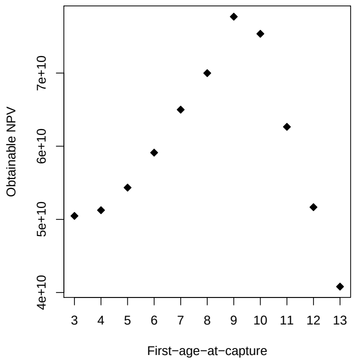

Figure 8: Obtainable NPV for given first-age-at-capture, linear recruitment

It is also informative to compare Figure 8 to Figure 5, which both plot the maximum obtainable profits at each first-age-at-capture. While the overall shape between these two curves is similar, their scale is very different. Moreover, the gain by deferring harvesting by one age class prior to the optimum is steeper and the drop by going too far (that is by selecting fish that are at least as old as 10 instead of 9 years) is less severe in the case where recruitment is endogenous (Figure 8) than in the case where recruitment is exogenous (Figure 5).

5.2 Discussion

In order to judge the robustness of these results on the model calibration, we shift the proportion of mature individuals at age by one and two years forward and backwards respectively. This decreases/increases the relative importance of the oldest age-classes for recruitment, and therefore provides for a larger/smaller unharvested spawning stock. When the fish mature earlier, more profits are obtainable, and when the fish matured later, less profits are obtainable. Yet these changes are small (roughly +/- 5%) and also the corresponding optimal effort does not change significantly. In particular, the optimal selectivity pattern is the same. The contribution of fecundity to the trade-off in selecting the right first-age-at-capture thus appears to be small, confirming the theoretical discussion from Skonhoft et al. (2010).

It therefore seems that managing growth-overfishing is more important than managing recruitment overfishing, in the sense that, at least for a species like the NEA cod, the current concern about recruitment-overfishing would be unnecessary, if growth-overfishing would be adequately managed. This does of course not mean that the process of recruitment is not important. Rather it means that correctly answering the question which fish should be harvested – in practice by adequately controlling gear selectivity – implies the protection of the spawning stock. But it does not work the other way around; protecting the spawning stock does not lead to an adequate protection of young and growing fish.

Often the argument to protect the old fish is brought forward, mainly out of a concern for big, old, fecund females that contribute over-proportionally to reproduction (Smith and Gopalakrishnan, 2010). Although sparing the young fish indeed implies the entire harvest is concentrated on few old age-classes, it is important to realize that changing the selectivity pattern implies that there are many more old fish around. Every age-class is more abundant under the optimally changed selectivity pattern (confer Figure 7). Nevertheless, one interesting aspect is that such a drastic change of the exploitation pattern could lead to an evolutionary response where cod grows slower or matures earlier, such that it can complete its entire life-cycle without ever entering the zone where it would be subject to fishing pressure (Jørgensen et al., 2009). However, our model neither includes the necessary detail nor does it cover the necessary time-horizon to fruitfully discuss fisheries-induced-evolution (but see Eikeset et al., 2010c).

In summary, the ability to "control" the recruitment process does not lead to different policies. If anything, it is more valuable to control the gear selectivity. Admittedly, both completely exogenous and completely deterministic recruitment are overstatements. In reality, there certainly is a connection from today's spawning stock to tomorrow's recruitment, but it is only one of many influences. Moreover, it is quite likely that there are decreasing returns to stock size, so that an increase in stock size does not necessarily lead to a proportional increase in recruitment. This effect, which is commonly called density-dependence, may also work at the individual level: due to e.g increased competition for food, the individuals may grow slower when there are more fish around. The following section will look into these aspects.

6 Density dependence

The projection of optimal harvesting policies leads to stock sizes that are significantly higher than today's. In particular, there are many more three to eight year old fish in the model ocean than it is presently the case. It is quite likely that there are penalties for high stock sizes in terms of density-dependence, but their exact nature is often uncertain or unknown. In order to study the effect of these processes on the character of optimal policies and on the obtainable efficiency gains, we model their occurrence in a general way, first only in the recruitment function, then only relating to individual weight-at-age, and finally in both recruitment and growth.

6.1 Modeling density-dependent effects...

...in the recruitment function

In the bio-economic literature that employs age-structured models, density dependence is generally assumed to occur in the recruitment function and to be either of the Beverton-Holt or the Ricker type, although more forms are discussed in the ecological literature (Myers, 2002). The Beverton-Holt recruitment function is of the general form $R = \frac{\alpha SSB}{1+\beta SSB}$, where the parameter α is the slope of the recruitment function in the origin. It is called the "shape parameter", whereas β is called "scale-parameter" since recruitment is increasing but tends to $\frac{\alpha}{\beta}$ as SSB grows large. In contrast, recruitment according to the Ricker function $R = \alpha SSB \cdot e^{\beta SSB}$ is declining towards zero when the spawning stock gets large.

Again, the parameter α is the slope of the function in the origin and β determines how fast the curve is turning downwards. Both functions are estimated on ICES data from 1946-2009 (by using the routine `nls` in the statistical program "R"). The regression results are given in Table 10. Refer also to Figure 1 (page 6) for a graphical illustration of the two functions and the range of observations.

Table 10: Regression results for Beverton-Holt and Ricker recruitment function

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
α_{BH}	1.9662	0.5243	3.750	0.000405
β_{BH}	-4.7895	0.6908	-6.934	3.50e-09
α_{Ricker}	3.4557	0.5726	6.036	1.13e-07
β_{Ricker}	-0.0017	0.0003	-5.165	2.98e-06

In the simulations, we add a random draw from the residuals of the estimations to the calibrated functional forms in order to obtain a somewhat similar range of recruitment values as in the data. To be precise, equation (1) is replaced by equation (8) and (9) accordingly.

$$n_{3,t} = \frac{1.9662 \cdot SSB}{1 + 0.0083 \cdot SSB} + \epsilon_{BH} \tag{8}$$

$$n_{3,t} = 3.557 \cdot SSB \cdot \exp(-0.0017 \cdot SSB) + \epsilon_{Ricker} \tag{9}$$

...in the growth function

Density dependence may however not only occur in the recruitment function, it may also occur in the growth function. North-East Arctic cod shows large variations in the weight-at-age. Figure 9 plots the distribution of weight-at-age from the years 1931-2005, which includes periods when cod was much more abundant and the age-structure within the stock was dominated by old fish.[12] It seems quite intuitive that growth is slower at high stock levels. The data indeed shows negative correlations between weight-at-age and abundance. The

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[12] The data is obtained from a long-term Virtual Population Analysis (VPA) performed by Hylen (2002) for the period 1931-2000. The first period of Hylen's estimates (1931-1945) complements the ICES estimates (1946-2005) in order to obtain the longest and most reliable data-set for estimates of weight-at-age.

correlations are strongest for the abundance of the respectively own cohort, which is consistent with earlier findings from survey data (Hjermann et al., 2004).

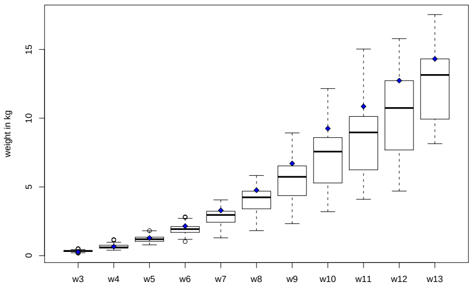

Figure 9: Boxplots of weight at age from 1932-2005, filled diamonds are average values from 1990-2005

However, the exact mechanism of density dependent growth in NEA cod is unclear. Ottersen et al. (2002) suggest an explanation according to which the negative relationship between abundance and growth is an effect of food competition, but an artifact of climatic variations: A strong inflow of Atlantic water into the Barents Sea is correlated with high recruitment, but the larvae are subsequently distributed far into the cold eastern Barents Sea. For the first years of their life, these fish find themselves trapped in regions which are unfavorable for growth. This mechanism could explain the strong intra-cohort but weak inter-cohort correlations between abundance and weight.

Nevertheless, we want to capture the potential for density-dependence in growth in a simple manner and therefore estimate the average weight-at-age when the cohort abundance is in the upper quartile of its distribution, when it is in the lower quartile of its distribution and when it is in between. This results in three different "growth functions", depending on the cohort size (Table 11).

Table 11: Density dependent weight-at-age

Age a	3	4	5	6	7	8	9	10	11	12	13+
$\underline{w}_a$ if $n_a \geq \overline{n}_a$	0.34	0.67	1.16	1.76	2.36	3.09	3.93	4.79	5.57	6.54	9.20
$\widetilde{w}_a$ if $\underline{n}_a < n_a < \overline{n}_a$	0.33	0.64	1.17	1.82	2.81	4.13	5.64	7.49	9.04	10.79	12.88
$\overline{w}_a$ if $n_a \leq \underline{n}_a$	0.34	0.72	1.34	2.21	3.40	4.80	6.64	9.23	10.97	11.99	14.15

With a density dependent feedback in place, there could be incentives to release pressure from the older age-classes. By reducing the abundance through higher effort or a lower first-age-at-capture, the remaining which are allowed to grow heavier. It is therefore particularly interesting to work out the contrast to a simulation where the weight-at-age is at its lowest level $\underline{w}_a$ regardless of the abundance. When there is no feedback from abundance to weight, the mechanism of "thinning" the stock is not available.

...in both recruitment and growth function

Finally, we combine density dependent effects in the recruitment and in the growth function. That is, equation (1) is replaced by equation (8) or (9), and weight-at-age is according to Table 11. These simulations present to some extent a lower bound on the estimates of efficiency gains from improving management: When there are penalties for high stock sizes both in recruitment and in individual growth, there is only so much to be had by increasing the stock.

6.2 Simulation results and discussion

This subsection discusses the results from the various simulations as presented in Table 12. For ease of comparison, we repeat the outcome of the baseline model in the first two lines. Then we show the profit-maximizing outcomes under Beverton-Holt (BH) and Ricker recruitment. Subsequently, we discuss the effect of density dependence in the growth function (ddw) and finally we present the outcome when density dependence is at work both in the recruitment and growth function (BH + ddw and Ricker + ddw). Figure 10 is an illustration of the maximum obtainable NPV at different first-ages-at-capture. It gives an additional idea how the different modeling assumptions shape the estimate of efficiency gains.

The Beverton Holt recruitment function is a relatively benign form of density-dependence: Even though the increase in recruitment is slowed down as the spawning stock increases, it is still positive. Moreover, its asymptotic value is higher than the mean of the observed recruitment, but lower than the value in the deterministic case. Hence, it is not surprising that the obtainable NPV is significantly larger than in the baseline model, but smaller than in the model discussed in section 5. Accordingly, also effort, harvest, and biomass are in between the random-recruitment model and the deterministic-recruitment model. The optimal choice of selectivity is the same as previously: 9 years. Again, controlling the system by choosing gear selectivity is relatively more important

Table 12: Overview of results with density dependence

Model	**scenario**	**policy**	**effort**	**select.**	**biomass**	**harvest**	**NPV**
baseline	only e	$e = 3.34\%x$	119	3	5 673	537	22.7
	e and s	$e = 5.50\%x$	311	9	5 656	1 012	32.4
BH	only e	$e = 2.25\%x$	113	3	5 053	893	29.5
	e and s	$e = 5.37\%x$	385	9	7 170	1 413	44.0
Ricker	only e	$e = 9.86\%x$	229	3	2 326	747	21.4
	e and s	$e = 10.06\%x$	291	6	2 740	852	23.9
ddw	only e	$e = 6.74\%x$	158	3	2 352	549	16.5
	e and s	$e = 7.91\%x$	210	6	2 650	625	18.0
BH + ddw	only e	$e = 5.96\%x$	169	3	2 844	688	20.6
	e and s	$e = 5.57\%x$	221	7	3 981	773	23.1
Ricker + ddw	only e	$e = 9.47\%x$	213	3	2 250	654	18.2
	e and s	$e = 9.86\%x$	235	5	2 393	699	19.5

than in the baseline case as there is the additional benefit through increased recruitment.

In contrast, when recruitment is governed by the Ricker function, an increased standing stock will after a certain point lead to a decreasing recruitment. This has, of course, a strong impact on the estimate of efficiency gains from improved management. In fact, as the peak of the Ricker recruitment function is – by construction – within the range of observed stock levels, there is almost no room for improvement over the status quo.[13] In spite of the small scope for efficiency gains (roughly 12%), it is particularly important to be able to control selectivity in this model. It allows to separate the immature from the mature part of the stock and concentrate harvesting on the latter. This makes immediate sense as the severe penalty introduced by Ricker recruitment is a function of the spawning stock, not the overall stock size.

Turning to the model with density dependence in the growth function, one expects that the introduction of a negative relationship between stock size and growth depresses the value of the fishery. In fact, if the effect were as strong as we

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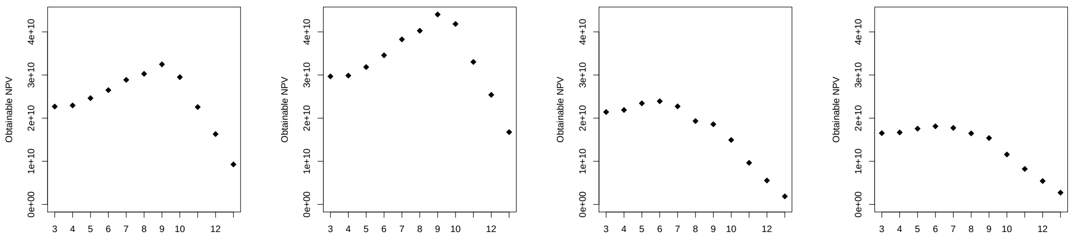
[13] A simulation of the current HCR with a fishing mortality of $F = 0.4$ yields a NPV of 20.4 billion Euro.

have modeled it, then there would be little room for improvement over the status quo. The NPV is below what was obtainable even with constraint selectivity in the base-line case. The optimal first-age-at-capture is also significantly younger, at an age of 6 years. A smaller selectivity could be optimal for two reasons: First, as the weight-at-age values are lower, the mortality discounted biomass of a given cohort will reach its peak earlier. And it can of course not be profitable to begin harvesting fish after their biovalue has begun to decline. Second, it might be optimal to begin harvesting earlier in order to release pressure from the standing stock. By removing individuals from the population, the remaining individuals can grow at a higher rate. In order to judge whether the earlier selectivity is due to a slower value growth in general, or due to an effect of “thinning”, we run a simulation where weight-at-age is set to its lowest value independent of cohort abundance. The exploitation pattern that maximized profits in this case is considerably lighter than in the density dependent case. Effort is lower (187 instead of 210 thousand units) and in particular the first-age-at-capture is higher (7 instead of 6), but still the profits amount to only 16.6 billion Euro (as compared to 18 billion Euro). It therefore appears that a “thinning” of the stock indeed takes place and leads to higher profits.

The outcomes from the simulations when density dependence is present in both recruitment and the growth function show that these two effects cancel each other to some degree: The profits are higher than when density dependence is present only in the growth function. However, the overall growth capacity of the stock is nevertheless depressed due to the penalties for high stock sizes. Consequently profits, harvest, and biomass remain relatively low and also the efficiency gains from choosing a larger mesh size are comparatively small.



(a) Baseline (b) BH (c) Ricker (d) ddw

Figure 10: Comparison of obtainable NPV at first-age-at-capture

In summary, Figure 10 shows the strong impact of modeling assumptions on the obtainable NPV and consequently on the most profitable policies. In particular Ricker recruitment and density dependent weights limit not only the overall biomass and harvest but also the magnitude of the efficiency gains from choosing gear selectivity. However, these results should be treated with caution. More than anything else, they indicate an interesting avenue for further research. The underlying mechanisms are uncertain, and our modeling approach is crude and likely to be a gross overstatement of the actual tendencies at work.

Nevertheless, the simulations do point to the potentially large implications of extrapolation model functions far outside the domain over which they were estimated. For example, the behavior of an optimization model with a Ricker recruitment function will be heavily influenced by the fact that recruitment tends to zero, in spite of no observations for large spawning stock sizes and the extreme prediction of zero asymptotic recruitment which is void of biological meaning. Still, this is a *catch 22*, as one cannot refrain from employing optimization models or scenario projections, both if one wants to make relevant policy recommendations and if one wants to fully explore the different aspects of age-structured bio-economic models. The researcher is thus only left with the option (and duty one might argue) to point to the uncertainties surrounding the modeling results.

In terms of a policy recommendation, it transpires clearly that it is important to use gear selectivity as an active choice variable for determining the harvesting pattern. It leads to considerable increases in profits under the whole suite of different biological models. While changing gear selectivity from its current level ($s = 3$) all the way to $s = 9$ may be overdoing it, there is little danger in going to a level of $s = 7$. This would still save the larger part of the obtainable efficiency gains when the world is close to the model with exogenous- or Beverton-Holt recruitment, and would not yet do any harm when the world is close to the model with density dependent weights or Ricker recruitment.

7 Limitations and further work

There are several limitations to our study that call for future work. First of all, we consider the fishery of a species which is characterized by several harvestable age-classes that grow in weight and value with age. Although this description is arguably valid for many commercially harvested species, there are also species for whose life-histories the present model is not applicable. Pacific salmon, to take a stark example, are mainly caught just before they enter the rivers in which they spawn. For these fisheries, the age-at-capture cannot be controlled at all, whereas allowing a sufficient number of fish to pass upstream so that they can reproduce is a question of vital importance. More generally, a pattern of slow growth and late reproduction decreases the likelihood that recruitment-overfishing could be avoided by controlling growth-overfishing. Furthermore, the model is probably not adequate for species that exhibit schooling behavior as this can have a significant impact on the harvesting technology.

Steinshamn (2011) has recently proposed a way of modeling general age-specific harvest functions which allows a flexible incorporation of intermediate cases between perfectly schooling and demersal fisheries. A fruitful avenue for further research might be to try to empirically apply his approach. Moreover, we have modeled the gear retention pattern as knife-edge selectivity. While this is a good caricature of trawl selection, it is clearly not a fitting description for gear types such has gillnets. Although the results intuitively carry over to other general selection patterns, further work should consider these in more detail.

Moreover, our study does not account for two of the most imminent biological facts: First, there is no such thing as a constant environment. It is indeed very likely that the fish react to a changing harvesting pattern, either through adapting their behavior (Jørgensen and Fiksen, 2006) or through an evolutionary response (Jørgensen et al., 2009; Eikeset et al., 2010a).

Second, there is no such thing as a single-species fishery. Although the Barents Sea food-web consist of rather few trophic levels, the intra-species interactions have an important effect on the stock dynamics (Hjermann et al., 2007). Additionally, the fishery itself is a multi-species fishery, although the harvest of the second most important species in terms of volume (saithe and haddock) is less than a third of cod harvest.[14] At least for the coastal fishery, it appears that the fishermen would not target cod the way they do were it not also for these smaller species (Jensen, 2007). Moreover, as cod, saithe, and haddock are to some extent substitutable products, intra-species interactions may also exist in the marketplace.

These aspects are important because radically changing the gear selectivity could imply that very few individuals of the other species can be retained in

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[14] Average harvest of saithe in 1990-2005 was 147 thousand tons, and the average harvest of haddock in 1990-2005 was 108 thousand tons. The average aggregate stock size in this period was 739 and 370 thousand tons respectively.

the net. While doing justice to the economic and biological aspects involved with a multi-species system is beyond the scope of this study, we provide a first impression by considering Table 13. Corresponding to Table 1 and 4, it gives the weight, price, and mortality discounted value of a fish entering age-class a. Note that these values are adjusted so that they relate to the corresponding age of cod.[15]

Although saithe is less valuable and grows slower than cod, and haddock does not attain large sizes at all, there still appears to be a considerable gain from changing the current selectivity pattern also for these species. A cohort of saithe has reached its highest value at an age of 8 years and haddock reach their highest value to what corresponds to a first-age-at-capture between 6 and 7 years. Hence, also from this perspective, a change of gear selectivity that would spare cod that are younger than 6 years is warranted.

Table 13: Weights, prices, & mortality discounted value for Saithe and Haddock

Age a	3	4	5	6	7	8	9	10	11	12	13+
w_{Saithe} (in kg)	0.65	0.97	1.48	2.02	2.65	3.26	3.93	4.95	5.59	6.14	7.22
p_{Saithe}	0.55	0.55	0.55	0.67	0.67	0.8	0.8	0.8	0.8	0.8	0.8
v_{Saithe}	0.37	0.43	0.52	0.69	0.73	0.85	0.83	0.83	0.75	0.66	0.62
$w_{Haddock}$ (in kg)	0.17	0.30	0.57	1.72	2.63						
$p_{Haddock}$	1.32	1.32	1.32	1.74	1.74						
$v_{Haddock}$	0.28	0.40	0.48	1.21	1.19						

Last but not least, we have not studied the potential threat of stock collapse. The stock-recruitment relationships we use do not feature critical depensation, nor do we estimate a hazard rate for crossing a potentially disastrous threshold. By assuming that recruitment is a random draw from past observations, the fishery is effectively provided with an external subsidy. Nevertheless, the optimal policies between the random and the deterministic scenario are nearly identical. In general, crossing a threshold below which recruitment is significantly or even irreversibly impaired is believed to happen at low stock sizes. Yet one of the

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[15] That is, the weight of a haddock in column "Age 4" is not the weight of a four year old haddock, but the weight of a haddock whose length would correspond to a 4 year old cod. Values for length-at-age are from ICES (2010, Table B5 p.313) and provided by Dag Hjermann (pers.comm). Saithe grows in length at a similar speed as cod (Bergstad et al., 1987). Natural mortality is conventionally 0.2 as for cod. Weight-at-age values for saithe and haddock are taken from ICES (2010), Table 4.6 and Table 5.3.3 respectively.

main implications of avoiding growth overfishing is a strong increase in overall abundance. The concern about stock collapse therefore reinforces our argument. Still, it has to be highlighted that we do not make a statement that recruitment is not an important process. To the contrary, it is the basis for the continued existence of fish stocks and its understanding remains a key scientific challenge (Olsen et al., 2011). However, we argue that its practical importance for fisheries management has been over-emphasized. It is more important to manage growth-overfishing.

8 Conclusion

Fisheries, as most renewable resources, involve both an important human and an important natural dimension. Their management should strive to take both dimensions adequately into account, highlighting the need for interdisciplinary studies. Here, we have explored the effects of age-specific harvesting at the example of North-East Arctic cod. Combining biology with economics points to the importance of managing growth overfishing. My findings suggest, that at least for species like cod, too much emphasis is placed on avoiding recruitment-overfishing. Targeting the right age-class could not only lead to considerable economic gains, but it could also contain the problem of recruitment-overfishing, so to say, *en passant*.

In contrast to much of the previous literature, we explicitly account for the structural uncertainty surrounding the biological model and run the simulations under a large suite of different model scenarios. Whether recruitment is exogenous or governed by a linear-, a Ricker-, or a Beverton-Holt function; whether growth is at its current average or a density-dependent function, it always pays to spare the youngest cohorts. A robust policy implication of this work is therefore to change the current selectivity pattern from $s = 3$ to at least $s = 6$, simultaneously increasing profits and stock abundance.

The remaining question then is, if the potential gains are as large as the study suggests, why hasn't selectivity been optimally controlled for the longest time? This is, in the end, a descriptive question, but there is good reason to believe that adequate age-specific harvesting does not emerge spontaneously: The "race to fish" extends to the dimension of age (Diekert, 2010). Moreover, even sharing a stock between two sovereign nations (such as the NEA cod is shared between

Russia and Norway) is often sufficient to dissipate a large part of the rent (Diekert et al., 2010a). The crucial role of the institutional setting currently receives high-profile attention (Costello et al., 2008; Heal and Schlenker, 2008; Worm et al., 2009; Gutierrez et al., 2011). Solving collective action problems still remains the biggest challenge for sustainable development. Yet this should not keep researchers from making suggestions to improve existing policies.

Acknowledgements

We would like to thank Anne Maria Eikeset (CEES, University of Oslo) and Per Sandberg (Fiskeridirektoratet, Bergen) for obtaining the panel on the Norwegian trawler fleet. The paper has benefited greatly from the discussions with A. M. Eikeset, D. Hjermann, A. Richter, C. Jørgensen, M. Heino, and S. I. Steinshamn. FKD gratefully acknowledges advice and support from Kjell Arne Brekke and Nils Chr. Stenseth and funding from the Norwegian Research Council, through the project "Socio-economic effects of harvest-induced evolution".

9 Appendix

9.1 Details on the economic part of the model

The basis of the economic data, which is provided by the Norwegian Directorate of Fisheries, is the annual survey of the Norwegian trawler fleet catching cod North of 62-degree latitude (Fiskeridirektoratet, several years). One part of the data has prior been analyzed by Sandberg (2006) and Richter et al. (2011). It spans the years from 1990 to 2000. The other part of the data is newly acquired and basically an extension of the Sandberg data to the years 2001-2005. To construct a cost variable, the 14 different entries of cost-components in the data (fuel, insurance, maintenance, etc.), are summed and corrected for inflation.[16] Note that all calculations and regressions are performed in terms of year 2000 Norwegian Kroner, but for ease of comparison,I report all results in year 2000 Euro.[17]

By inspecting the distribution of the percentage that cod contributes to total harvest (Figure 11), it becomes clear that, for the main part of the sample, cod makes up less than half the harvest. I drop all observations where cod is clearly undirected bycatch (i.e. cod makes up less than 2% of the harvest; 30 observations out of 864).

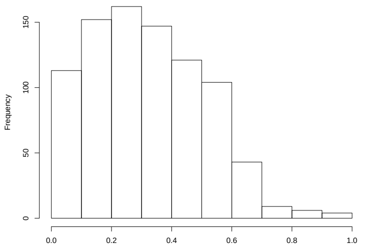

Figure 11: Histogram: share of cod in total harvest

Several candidates exits when selecting the best proxy for “effort”. As it measures of the intensity of fishing, it should include an element of the time that is spent harvesting (Gulland, 1983). Moreover, if boat size is a significant determinant of the harvesting process, size should be included in the effort proxy. Boat size could be captured by either length or tonnage. After analyzing the dataset, We choose the latter as it correlates closer with harvest and costs. One unit of effort is therefore one unit of boat tonnage effectively catching cod for one day. 48 observations have no information on tonnage, so that we are left with a panel of 786 observations from 141 different boats over a period of 16 years (on average 5.6 observations per boat, some boats are observed in all years).

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[16] The Commodity price index for the industrial sectors from the Norwegian bureau of statistics (SSB) were used. `http://statbank.ssb.no/statistikkbanken/Default_FR.asp?PXSid=0&nvl=true&PLanguage=1&tilside=selecttable/hovedtabellHjem.asp&KortnavnWeb=vppi`.

[17] The employed exchange rate is 1 EUR = 8.1109 NOK; see `http://www.norges-bank.no/templates/article____56181.aspx`

Estimation of parameters in the harvest and cost function

The crux of estimating the parameters in the age-specific harvest function (equation (4) on page 12) is that age-specific data is not available at the boat level. This means that it is not possible to estimate equation (4) directly.[18] We take the following approach to overcome this: Let J be the total number of boats in the fishery. The harvest from a given boat j is aggregated over all age-classes in the data from Fiskeridirektoratet: $h_j = \sum_a h_{a,j}$. The ICES data is aggregated over all boats, but available in age-specific format $h_a = \sum_j h_{a,j}$ as well as in total $h = \sum_a \sum_j h_{a,j}$ (see Table 3.9 and 3.10 in ICES, 2010, pp.175). By assuming that all boats have the same selectivity pattern and using the share of each boats harvest in total harvest, we are then able to calculate the individual age-specific harvest as $h_{a,j} = \frac{h_a}{h} h_j$.[19]

Having a panel of boats, it is possible to account for individual heterogeneity. Most importantly, the (unobserved) ability of the fishermen is omitted from the definition of effort (Squires and Kirkley, 1999). Since the panel at hand is broad (141 boats), but short (16 years at maximum), a fixed-effects model would over-emphasize large-sample consistency for estimation efficiency. Moreover, we are interested in the harvest function of the population, not in the function for the boats in this specific sample. We therefore estimate equation (4) by a random-effects model (the routine `lme` in the statistical program "R"). By using a dummy variable in front of each age-specific biomass, we obtain the age-class specific parameters β_a, but the effort elasticity α and the boat-specific intercept q remain the same for all age-classes.

$$\begin{gathered} \log h_{a,j,t} = q^* + q_j + \alpha \log e_{j,t} + D\beta_3 \log x_{3,t} + D\beta_4 \log x_{4,t} + ... + \varepsilon_{a,j,t} \\ q_j \sim \mathsf{IID}(q^*, \sigma_q^2), \quad \varepsilon_{s,j,t} \sim \mathsf{IID}(0, \sigma^2), \quad \varepsilon_{s,j,t} \perp q_j \perp e_{j,t} \perp x_{s,t} \end{gathered} \tag{10}$$

The regression results are given in Table 14. As harvest is not found to be linear in effort, it is impossible to aggregate from the boat level to the fleet level. Therefore, the model is calibrated with the estimates for the average boat in the sample and effort in the simulation is scaled up so that it replicates the size of the actual harvest.[20]

Similar to effort above, we are only interested in the share of costs which is caused by catching cod. Therefore, the total cost are weighted by the boat-specific share of cod in the total harvest. With this definition, costs are linear by construction. But there are no signs of non-linearity in the underlying relationship. Throughout, a linear specification gave the best fit. In spite of a constant marginal relationship between costs and effort, the marginal

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[18] This is probably the reason why – to the best of our knowledge – an age-specific harvest function has not been empirically estimated yet. However, Sumaila (1997) employs a similar idea to arrive at age-specific catchability coefficients, but he assumes linearity in effort, and uses data from only one year.

[19] In fact, thanks to Bjarte Bogstad and Kjell Nedreaas (both at the Institute for Marine Research, Bergen) we were able to obtain age-specific harvest data from only the Norwegian trawler fleet (pers.comm.). However, due to the small sample size ($\sim$ 13 boats) the estimates from this dataset are significantly less precise and the model could only explain a fraction of the variance explained by the regressions on ICES data.

[20] The number of boats is set to 200, but a value of $\alpha = 0.9$ means that the model is not very sensitive to this assumption.

Table 14: Regression result for harvest function

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
q	-16.701	0.090	-184.9760	0
log e	0.902	0.007	122.8770	0
log x3	0.733	0.006	127.4131	0
log x4	0.875	0.006	158.8186	0
log x5	0.932	0.005	173.3542	0
log x6	0.949	0.005	175.4130	0
log x7	0.956	0.006	172.7147	0
log x8	0.957	0.006	165.4993	0
log x9	0.948	0.006	154.6800	0
log x10	0.937	0.007	142.9521	0
log x11	0.922	0.007	130.6130	0
log x12	0.916	0.008	120.8221	0
log x13+	0.928	0.008	116.9850	0

relationship between costs and harvest is increasing: For $\beta > 0$, the stock dependency makes it excessively costly to harvest the last fish in the ocean. The regression results for the cost function (where the intercept is suppressed since it would have the unwanted effect of fixed- or set-up cost in the model simulations) are given in Table 15.

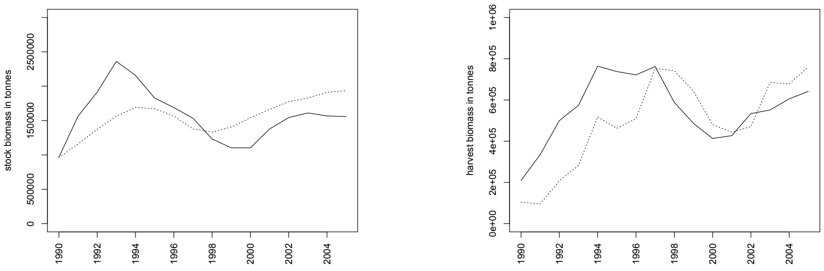
Table 15: Regression result for cost function (in year 2000 NOK)

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
tonnage-days	63.4611	0.8368	75.84	<2e-16

Validation

In order to validate the bio-economic model, we compare the actual development in the historic fishery with the model predictions. Figure 12a shows the development of NEA cod biomass from 1990-2005, while the dotted line shows the predictions from the biological part of the model. These predictions are obtained by simulating the stock, starting from the initial biomass-at-age in 1990, and taking recruitment and harvest-at-age from the data. Clearly, there is some error from using the average weight-at-age values and from employing a natural mortality pattern of 0.2 for all age-classes except the oldest, but the overall trend can be captured.

Similarly, Figure 12b shows the development of the harvest from 1990-2005, compared with the predictions (dotted line) when reading in the recruitment values and taking the effort in a given year to be the average from the sample in that respective year times 200 (the assumed number of boats in the fishery). The error in the first half of the validation period could stem from the inaccuracy in the biological part of the model or from the fact that the sample size of the economic panel is significantly smaller in 1990-1995 than in 2000-2005. Still, also the complete bio-economic model succeeds in roughly replicating the overall development.



(a) Stock, observed vs. predicted

(b) Harvest, observed vs. predicted

Figure 12: Model validation

It should be emphasized that we do not aim at calibrating a model *of* the NEA cod to fit past observations as accurately as possible, but at calibrating a generic model *on* the NEA cod to make inferences about the implications of different policy options.

9.2 Computer code

The following presents an edited version of the R-code used to obtain the simulation results. By accordingly calibrating the generic functions it can easily be amended to simulate the development of other fisheries as well. The average computing time on a standard desktop computer is 1-2 hours per rule. We provide the code for the feedback effort rule (rule 3) and the fixed selectivity rule (rule A) of the baseline model here.

At first, parameters and control space are supplied:

```
T <- 100 #Time length
Nagecl <- 11  #Number of different age-classes
Simul <-500 #N simulations
Numberboats <- 200 #N boats
e.min <- 1500 #Min effort in sample
e.max <- 2*500000 #2 times max effort in sample

# control space:
A  <- 51 #N of different proportions for effort
a.min <- .01 #Min effort proportion
a.max <- .1 #Max effort proportion
f <- seq(a.min,a.max,length=A) # factor of proportionality
I  <- 11 #N of different selectivity policies
CS  <- A*I # control-space dimension

# Loading parameter estimates
source('path to file')
```

Then the program loops, for a given rule, through a grid of policies, for 100 time-steps, repeating each simulation 500 times (prior to this, a number of internal variables for storing results are defined, which are omitted).

```
### For each allowable effort value,
for (a in 1:A) {

### For each selectivity scenario
for (i in 1:I) {

sel <- Sel[i,] #e.g. Sel[3,] = c(0,0,1,1,1,1,1,1,1,1,1)

### For each simulation
for (s in 1:Simul) {

# initial population randomly drawn from observed stock
index_ini <- sample(62,1)
x_ini <- as.double(stock[index_ini,2:12])
n <- x_ini/w

### For each time step
      for (t in 1:T) {

        ### ABUNDANCE
        n.begin <- as.vector(Phi%*%n) #Phi is survival matrix
        n.begin[1] <- sample(obsRecr,1)   # random recruitment

        ### BIOMASS - growth
        x <- n.begin*w #calculates biomass-vector in tonnes
        Biomass[,t] <- x #record the age-specific biomass
```

Concerning the harvest function, care has to be taken that harvest is neither negative nor exceeds the available biomass.

```
            ### HARVEST
        effort <- f[a]*sum(x) # effort

        h.prelim <- Numberboats*(q*sel*(effort^alpha))*(x^gamma)
        h <- rep(0,Nagecl) # h is total fishery harvest
        for (k in 1:Nagecl) {
          if (h.prelim[k] >= 0) {#is harvest positive?
            if (h.prelim[k] < x[k]) { # is harvest smaller than x?
              h[k] <- h.prelim[k] # all is OK
            } else {h[k] <- x[k]} #harvest \leq biomass
     } else {h[k] <- 1}
        }
        Harvest[,t] <- h #recording harvest at time t

        ### PROFITS
        profits <- sum(price*h) - Numberboats*(cost*effort) #inst. Profit
        Profits[t] <- profits # recording inst. profits
        discPrf[t] <- delta^t*profits # recording discounted profits
        ###-----------------###

        x.begin <- x-h
n <- (x.begin)/w #update the n-vector

     } # end t-loop
     ###-----------------###

NPV <- sum(discPrf)
```

Finally, mean and std.deviations are calculated on-line (here reported for NPV) and the value of the maximum NPV that was obtained so far is stored separately and all remaining measures are collected in a list.

```
     online = online + 1

     del <- NPV - meanNPV
```

```
     meanNPV <- meanNPV + del/online
     M2 <- M2 + del*(NPV - meanNPV)
     varNPV <- M2/(online - 1)


    } # end s-loop
###-----------------###

# keeping only the best and one specific
if(meanNPV > maxNPV){
maxNPV <- meanNPV
max.avBiom <- meanBiomass
max.avHarv <- meanHarvest
max.specBiom <- specBiomass
max.specHarv <- specHarvest
}

# record effort- and selectivity values of the scenario
SRef[count,1] <- meanNPV
SRef[count,2] <- sqrt(varNPV)/sqrt(Simul)
SRef[count,3] <- f[a] #epol
SRef[count,4] <- meanEffort
SRef[count,5] <- meanSelect
SRef[count,6] <- mean(colSums(meanHarvest))
SRef[count,7] <- mean(colSums(meanBiomass))

# go to the next policy scenario:
count <- count + 1

}# end i-loop
}# end e-loop
```

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