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Abstract: The importance of a fish stock's age structure is increasingly recognized in economics and ecology. Still, current policies predominately rely on measures of the aggregate biomass. Here, a detailed bio-economic model is calibrated on the Northeast Arctic cod (*Gadus morhua*) fishery to assess the efficiency gains from controlling gear selectivity and explore them under a suite of different scenarios. While the absolute size of economic gains varies drastically with the particular biological modeling assumptions, the relative economic gains from age-differentiated management show that it is high time to move beyond traditional reference points.

Introduction

All over the world, many fisheries fail to generate their full potential value as the fish stocks' age structure is not properly managed. This paper develops a generic, yet detailed, model to provide an "estimate of efficiency gains from [age-specific] optimal harvesting compared to currently applied biological reference points" (Tahvonen 2009*a*, p. 297) and to investigate the sensitivity of the model results on the underlying biological assumptions.

Although the importance of controlling for age-specific[1] selectivity has recently been highlighted in the theoretical economic literature (Tahvonen 2009*a*, 2009*b*; Skonhoft et al. 2012), and in spite of the continuing increase of detailed empirical bio-economic models (e.g., Stage 2006; Bjørndal and Brasão 2006; Smith et al. 2008), there are to date only very few empirical studies that specifically investigate the effect of changing gear selectivity.[2] Similarly, most bio-economic studies have generally assumed some specific form of the recruitment function without further discussion of its implications.

Clearly, the detrimental effect of harvesting fish that are still growing strongly has been known for a long time. It was already a central issue in Petersen's report (1893), and gear selectivity was high on the agenda during the rise of modern fishery science (Allen 1953; Beverton and Holt 1957; Turvey 1964). Today, 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. Owing to the selective property of fishing gears, very few fish survive to grow old and large, implying a pronounced shift of the age composition of harvested stocks. 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. 2010), these changes may be irreversible (Stenseth and Rouyer 2008).

Nevertheless, management advice is predominantly given in terms of aggregate biomass. Surely, most management schemes do include some sort of gear regulation or minimum size limits, but these are mostly set ad hoc and are far from optimal (Froese et al. 2011). The preferred tool in most fisheries is the setting of total allowable catch (TAC) quotas. Based upon an estimate of the aggregated stock biomass, 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?"

The main contribution of this work is to highlight the economic gains from adequately considering gear selectivity. I develop a generic model that is calibrated to the Northeast Arctic cod fishery (NEA cod, *Gadus morhua*), which is the world's largest and most valuable cod fishery. Concentrating on this specific case allows me to make concrete statements on the size of efficiency gains as well as it allowing the exploitation of high quality data over a timespan that is rarely found in the literature. At the same time, the present combination of fundamental biological and economic thinking generates important insights that generalize more broadly to

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[1]Note that, 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), and **age** as such is often of subordinate relevance. 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 (1 year later, a given fish will be 1 year older). Moreover, data for fish stocks is routinely reported in age, not size.

[2]Sun et al. (2010) and Maunder et al. (2011) provide an evaluation of the economic losses due to the inefficient employment of purse seine and longline effort in the international tuna fisheries. Diekert et al. (2010*a*, 2010*b*) consider the mixture of passive and active gear and harvesting from the Russian and the Norwegian fleet in the Northeast Arctic cod fishery, respectively.

those fisheries where the individual fish are growing in value with age–size. A further contribution is the incorporation of an estimated age-specific harvest function in the model. The results from the baseline model suggest that the mean annual profits from following the current management rule are €197 million (Euro). The annual profits from choosing effort optimally (but leaving selectivity as it is now) are €227 million. In contrast, the profits from choosing both effort and selectivity optimally are €324 million.

The other core aspect of this study is to point out that the choice of the underlying biological model structure has a relatively small effect on the optimal age-at-first-capture, but it has a strong effect on the absolute size of the economic efficiency gains. The simple truth of the matter is that almost all bio-economic studies consider only that specification of the recruitment function that gives the best fit over the domain of observed values. The extrapolation of optimal harvesting strategies will, however, be strongly influenced by the asymptotic properties of these curves. When recruitment is governed by a Ricker-type relationship, the gains from changing selectivity amount to, on average, €3.5 billion over a hundred-year time horizon. In contrast, when recruitment is governed by a Beverton–Holt relationship, these gains sum to €20.7 billion over a hundred-year time period.

In synthesis, this study 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. I provide an overview of the simulation model and procedure (details on the calibration and the numerical implementation can be found in Appendix A), and subsequently, the results are presented. I show that these results are insensitive to changes in economic parameters, but that the size of the efficiency gains depends on the respective biological scenario. I then point to the policy implications of these simulations and discuss how far they may continue to hold also for different fisheries or when more complex social and ecological aspects are taken into account.

Materials and methods

To provide an estimate of the economic efficiency gains from better age-specific management and to investigate the sensitivity of the results on the underlying biological assumptions, I develop an age-specific biological model of a fish population and couple it with an economic harvesting model. The combined bio-economic model is calibrated on the Norwegian cod fishery in the Barents Sea. The calibrated model is simulated for a large suite of different harvesting policies, and their performance is evaluated in terms of the obtained net-present-value (NPV, the discounted sum of annual profits over a given time horizon).

The cod stock in the Barents Sea was chosen as model species because it is now the largest cod stock in the world, supporting one of the most valuable fisheries (FKD 2011). Owing to its importance, the fish stock and its fishery is thoroughly researched.[3] It is jointly managed by Russia and Norway. The total annual harvest is currently around 500 000 tonnes, taken both by a conventional coastal fleet (30%) and an ocean-going trawler fleet (70%) (ICES 2010).

For the calibration of the economic part of the model, I concentrate on the Norwegian trawler fleet because of access to a unique dataset of individual boats from the Norwegian Directorate of Fisheries.[4] The main part of the model is calibrated for the period 1990–2005.

Simulation procedure

For a given harvesting policy, the bio-economic model is simulated for 100 discrete time steps, each representing 1 year. The sequence of events within one model year is recruitment, natural mortality, growth, and harvest.[5] The latter links the biological submodel, describing the stock development, with the economic submodel, describing how a given policy for choosing effort and selectivity maps into harvest and profits.

The program R (R Development Core Team 2011) was used to simulate the development of the fishery and record its performance. The objective to maximize the NPV is a problem of optimal control, which I — strictly speaking — do not solve with my approach. The sheer dimensionality of the state-space prohibits finding the globally optimal path among all feasible paths. Instead, the routine explores a large set of (feedback) policies from which it picks that combination of control variables that, on average, yields the highest NPV.[6] For each policy, the simulations of the model fishery are replicated 500 times. The grid of evaluated policies is consecutively narrowed until the mean NPV from the three best policies differs by less than one standard deviation. When presenting the results, I concentrate on the subset of policies that consistently yielded the highest NPV. (The full set of simulation results is described in Appendix A, and the computer code is available as supplementary material[7] to this article.)

The economic submodel

Mathematically, NPV is described by eq. 1. T is the end of the time horizon, here 100 years. The discount factor δ is set to 0.95, implying a discount rate of 5%. (I investigate the sensitivity of the results for a range of discount rates between 2% and 10%.) Profits π at time t are a function of effort e_t, selectivity s_t, and the fish stock x_t.

$$(1) \qquad \text{NPV} = \sum_{t=0}^{T} \delta^t \pi_t(e_t, s_t, x_t)$$

Profits can be written as eq. 2, where $\boldsymbol{p}$ is a vector of age-specific prices (assumed constant, see the discussion in Appendix A), and $\boldsymbol{h}$ is a vector of age-specific harvest (which is, again, a function of effort e_t, selectivity s_t, and the fish stock x_t). c denotes the cost per unit of effort.

$$(2) \qquad \pi_t = \boldsymbol{p}\boldsymbol{h}(e_t, s_t, x_t) - ce_t$$

The biomass of the fish stock x_t is the sum of the biomass of all cohorts that are 3 years and older (NEA cod are currently recruited

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[3]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. (2010a, 2010b), Eikeset et al. (2013), and Richter et al. (2011).

[4]Fiskeridirektoratet: Lønnsomhetsundersøkelser for helårsdrivende fiskefartøy. Dataset obtained through Per Sandberg (personal communication).

[5]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).

[6]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, cyclical solutions (pulse fishing) are also discussed in the literature (Hannesson (1975); see Diekert et al. (2010b) for a demonstration of this mechanism in NEA cod). My approach cannot capture these. This is in fact intentional, since pulse fishing is often a response to inadequate gear selectivity, while I 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 when gear selectivity is appropriate.

[7]Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfas-2012-0471.

to the fishery when they are 3 years old). In other words, age a runs from $a = 3$ to $A = 13+$, where the oldest age-class A collects all individuals of age 13 and above.

The following paragraphs discuss the harvest function, which is the heart of the bio-economic model. In fact, the cod fishery of the Barents Sea is a multispecies fishery. Saithe (i.e., pollock, *Pollachius virens*) and haddock (*Melanogrammus aeglfinus*) are, after cod, the most important species in terms of harvested volume.[8] The boats can therefore be characterized as joint-input, multi-output firms, where a common mix of inputs is used to produce several outputs (Squires, 1987; Jensen, 2007). In reality, fishing boats derive revenue from landing other species than cod as well, and avoiding to catch small cod implies that also small saithe are less likely to be caught. While a full biological and economic multispecies model is beyond the scope of this study, I do shed some light on these aspects in the Discussion.

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. The value of α tells how much harvest increases when effort increases by one unit. Lastly, q is the "catchability coefficient", which basically translates a given stock biomass into harvestable biomass.

However, this interpretation is problematic, as the "catchability" depends both on the targeting behavior of the fisher 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 either because the fisherman did not find it or 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 that age-classes are harvested is to premultiply the harvest function with the probability of being retained in the gear, conditional for a given age (selection curves are to a large extent available from the published literature; see Millar and Fryer 1999). This approach has been used by Diekert et al. (2010a, 2010b). It allows the isolation of the selectivity pattern of the gear, but 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 stock elasticity retains its property when substantially fewer age-classes are selected.

Another way of explicitly modeling the choice that 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, see Appendix A). The interpretation is that effort produces an amount of water that 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.

This type of knife-edge selectivity is of course a strong simplification. It brushes over other determinants of the selection pattern

such as the temporal and spatial targeting behavior of the fishermen. Moreover, it implicitly assumes zero discard mortality. An alternative modeling approach could have been to assign a positive discard mortality to those age-classes that are not targeted and to explicitly state intermediate values of the retention probability. However, reliable estimates for these parameters are difficult or impossible to obtain (especially for the counterfactual simulations of high values of s). The current modeling approach greatly enhances the transparency of the model. Importantly, it means that the translation of stock biomass to harvestable biomass for a given age-class does not depend on the other selected age-classes.

The harvest equation is then given by eq. 3, where I use a matrix of indicator variables i that take the value of zero for $a < s$ and the value of one for $a \geq s$.

$$(3) \quad \boldsymbol{h} = \begin{bmatrix} i_3 & 0 & 0 \\ \vdots & \ddots & \vdots \\ 0 & 0 & i_A \end{bmatrix} q e^\alpha \begin{bmatrix} x_3^{\beta_3} \\ \vdots \\ x_A^{\beta_A} \end{bmatrix}$$

where $\begin{cases} i_a = 0 \text{ for } a < s \\ i_a = 1 \text{ for } a \geq s \end{cases}$

The biological submodel

The biological submodel consists of a recruitment function R, the specification of natural mortality ϕ_a and fishing mortality, and the description of the mean mass-at-age w_a. Mathematically, the model is described by eqs. 4–6, where $n_{a,t}$ is the number of fish of age-class a at time t.

$$(4) \quad n_{3,t} = R$$

$$(5) \quad n_{a,t} = (1 - \phi_{a-1})n_{a-1,t-1} - \frac{h_{a-1,t-1}}{w_{a-1}} \quad \text{for } a = 4, \ldots, A - 1$$

$$(6) \quad n_{A,t} = (1 - \phi_{A-1})n_{A-1,t-1} - \frac{h_{A-1,t-1}}{w_{A-1}} + (1 - \phi_A)n_{A,t-1} - \frac{h_{A,t-1}}{w_A}$$
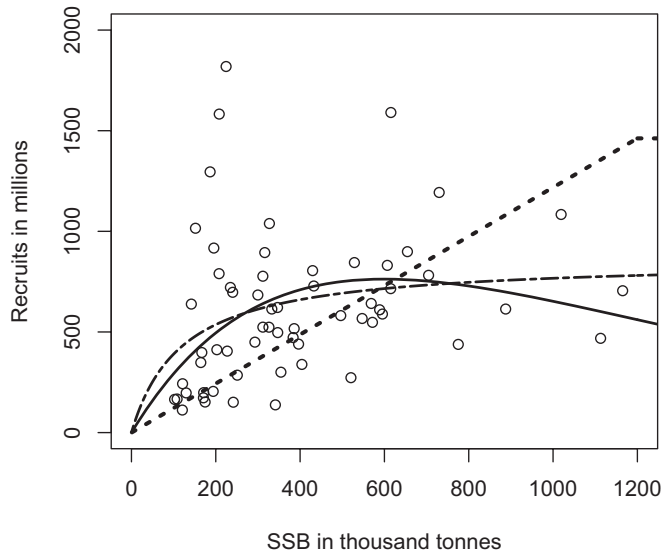
Figure 1 illustrates the large variability in recruitment; no stock–recruitment relationship is directly discernible. For the baseline model, I therefore assume that recruitment is exogenous, as in the classical analysis of Beverton and Holt (1957). Specifically, R is an independent and identically distributed draw from all observed recruitment values between 1946 and 2009 (taken from table 3.25 in ICES 2010, p. 209). This implies that recruitment is completely independent of the size of the spawning stock, so that 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 by protecting the overall size of the spawning stock. I therefore simulate a suite of scenarios with an explicit link between the standing stock and recruitment. Since this allows to control recruitment by controlling the overall size of the spawning stock, it is not clear whether it will be equally valuable to change the current selectivity pattern. To contrast the baseline model, where recruitment is exogenous, I first deliberately overstate the case of endogenous recruitment by assuming that it is a deterministic function. Recruitment is accordingly proportional to the spawning stock biomass (SSB)[9] over the domain of observed values and constant at its highest level thereafter (which is in fact in line with

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[8]The mean harvest between 1990 and 2005 was roughly 150 and 100 thousand tonnes for saithe and haddock, respectively. The corresponding value for Atlantic cod is roughly 500 thousand tonnes.

[9]The spawning stock biomass is defined as the aggregate biomass of all mature individuals: SSB = $\sum_{a=3}^{A} w_a n_a \text{mat}_a$, where mat_a is the proportion of mature fish at age a.

Fig. 1. Spawning stock biomass and observed values of recruitment. Modeled recruitment functions: linear = dotted line, Beverton–Holt = dashed–dotted line, Ricker = solid line.

Fig. 2. Boxplots of mass-at-age from 1932 to 2005; filled diamonds are mean values from 1990 to 2005. The x axis indicates ages 3 to 13.

of mass-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.[10] Although it seems intuitive that growth is slower at high stock levels and mass-at-age is indeed negatively correlated with abundance, the causal mechanism for NEA cod is unclear (Ottersen et al. 2002). In one set of scenarios, I therefore agnostically include possible density-dependent effects by estimating the mean mass-at-age when the cohort abundance is in the respective upper, lower, or middle quartiles of its distribution. This results in three different "growth functions", depending on the cohort size.

Results

Table 1 gives an overview of the results from the best-performing policies under the different scenarios.

The first column of Table 1 indicates the respective model employed, where "Baseline" refers to the scenario with random (exogenous) recruitment. The "Linear" scenario is when recruitment is endogenized and — to overstate the case — assumed to be a deterministic function of SSB. "BH" and "Ricker" relate to scenarios where recruitment follows a Beverton–Holt or a Ricker recruitment function, respectively. Mass-at-age is constant in all of these scenarios. Under the "ddw" scenario, mass-at-age is density-dependent, and recruitment is either random in the baseline case or follows a Beverton–Holt or Ricker recruitment function.

The second column refers to the respective scenario in terms of admissible control variables: a simulation of the current policy "HCR", a simulation where only effort is a choice variable "Only e", or a simulation where both effort and selectivity are choice variables "e and s". While the comparison of the HCR with the Only e scenario indicates the economic gains from improving on the current management rule, the comparison of the Only e with the e and s scenario highlights the additional gain from adequately controlling gear selectivity. The column "Effort policy" gives the feedback policy that maximized NPV and the implied mean effort values (in units of thousand tonnage-days). The column "Select." displays the chosen selectivity pattern, and the fifth and sixth column respectively give the mean biomass and harvest values (in units of thousand tonnes).

The last three columns present the economic performance criteria. "NPV" refers to the mean net-present-value, given in billion Euro, over a 100-year time period. The column "ttbe" (time-to-break-even) illustrates the trade-off between short-term losses and long-term gains from a changed selectivity pattern. It refers

the Leslie-matrix model). Hence, the data are fitted to a linear regression forced to pass through the origin, replacing eq. 4 by eq. 7.

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

In two further scenarios, I assume that recruitment either follows a Beverton–Holt or a Ricker recruitment function. In the bio-economic literature that employs age-structured models, density dependence is generally assumed to occur in recruitment and to be of one of these two types, although more forms are discussed in the ecological literature (Myers 2002). That is, eq. 4 is replaced by eqs. 8 or 9 for Beverton–Holt or Ricker recruitment, respectively. (In the simulations, a random draw from the residuals of the respective estimations is added to the function value to obtain a similar range of recruitment values as in the data.)
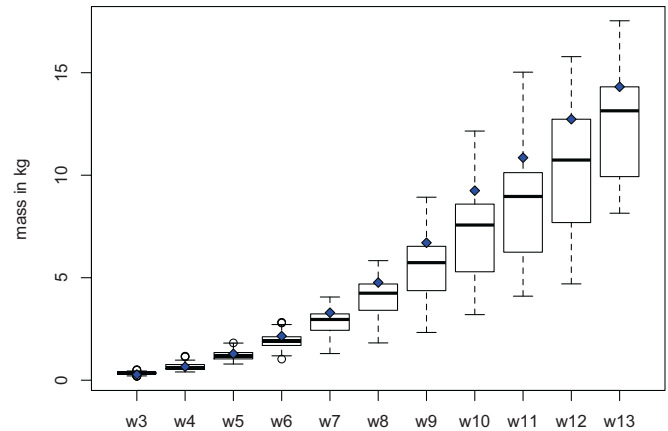
$$(8) \quad n_{3,t} = \frac{1.9662 \cdot SSB}{1 + 0.0083 \cdot SSB} + \epsilon_{BH}$$

$$(9) \quad n_{3,t} = 3.4557 \cdot SSB \cdot \exp(-0.0017 \cdot SSB) + \epsilon_{Ricker}$$

The development of an age-class from one year to the next is given by eqs. 5 and 6. 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 eq. 5) minus those that have been harvested (the second term on the right-hand side of eq. 5; since harvest h is specified in terms of biomass, it has to be divided by the age-specific mass to be given in terms of numbers). Equation 6 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.

The specific values for mass and natural mortality are reported in Appendix A. In one set of scenarios, mass-at-age will simply be the mean values from 1990 to 2005, so that the biological and economic model are calibrated on the same time period. NEA cod shows large variations in mass-at-age; Fig. 2 plots the distribution

[10]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 dataset for estimates of mass-at-age.

Table 1. Overview of the central simulation results.

Model	Scenario	Effort policy	Select.	Biomass	Harvest	NPV	ttbe	ttss
Baseline	HCR	$F = 0.4$; $\bar{e} = 197$	3	2 381	668	19.7	—	—
	Only e	$e = 3.34\%x$; $\bar{e} = 119$	3	5 673	537	22.7	—	—
	e and s	$e = 5.50\%x$; $\bar{e} = 311$	9	5 656	1 012	32.4	2.84	3.03
Linear	HCR	$F = 0.4$; $\bar{e} = 218$	3	2 347	721	23.3	—	—
	Only e	$e = 1.72\%x$; $\bar{e} = 135$	3	9 900	1 498	50.4	—	—
	e and s	$e = 3.52\%x$; $\bar{e} = 303$	9	12 067	2 445	77.6	3.46	11.75
BH	HCR	$F = 0.4$; $\bar{e} = 230$	3	2 542	800	23.2	—	—
	Only e	$e = 2.25\%x$; $\bar{e} = 113$	3	5 053	893	29.5	—	—
	e and s	$e = 5.37\%x$; $\bar{e} = 385$	9	7 170	1 413	44.0	3.45	5.64
Ricker	HCR	$F = 0.4$; $\bar{e} = 222$	3	2 327	716	20.4	—	—
	Only e	$e = 9.86\%x$; $\bar{e} = 229$	3	2 326	747	21.4	—	—
	e and s	$e = 10.06\%x$; $\bar{e} = 291$	6	2 740	852	23.9	1.63	1.99
ddw	HCR	$F = 0.4$; $\bar{e} = 195$	3	2 101	559	15.4	—	—
	Only e	$e = 6.74\%x$; $\bar{e} = 158$	3	2 352	549	16.5	—	—
	e and s	$e = 7.91\%x$; $\bar{e} = 210$	6	2 650	625	18.0	1.38	1.26
BH + ddw	HCR	$F = 0.4$; $\bar{e} = 228$	3	2 218	665	17.7	—	—
	Only e	$e = 5.96\%x$; $\bar{e} = 169$	3	2 844	688	20.6	—	—
	e and s	$e = 5.57\%x$; $\bar{e} = 221$	7	3 981	773	23.1	2.48	2.58
Ricker + ddw	HCR	$F = 0.4$; $\bar{e} = 224$	3	2 174	646	17.1	—	—
	Only e	$e = 9.47\%x$; $\bar{e} = 213$	3	2 250	654	18.2	—	—
	e and s	$e = 9.86\%x$; $\bar{e} = 235$	5	2 393	699	19.5	1.73	1.23

Note: Select., the chosen selectivity pattern; NPV, net-present-value; ttbe, time-to-break-even; ttss, time-to-steady-state; BH, Beverton–Holt; ddw, density-dependent mass; HCR, harvest control rule; e, effort; s, selectivity; F, fishing mortality.

the time it takes, on average, to make more profits than implied by the current management rule. "ttss" (time-to-steady-state) refers the time it takes, on average, for profits to enter for the first time the stochastic steady state.[11]

Increased gains from better management by appropriate selectivity

The results from the baseline model suggest that the obtainable NPV from following the current management rule is €19.7 billion, the NPV from choosing effort optimally, but leaving selectivity as it is now is €22.7 billion, and the NPV from choosing both effort and selectivity optimally is €32.4 billion. In other words, there is a gain of 42% from changing selectivity (nearly €10 billion over a 100-year time span). To put this in a more practicable perspective, the change in gear selectivity implies an annual gain of roughly half a million Euro per boat.

The management changes involve a trade-off between short-term economic losses while the stock is built up and long-term gains from an improved resource stock. Figure 3 illustrates this trade-off for different selectivity policies. The thin, horizontal black line in the figure shows the mean profits under status-quo simulation. Clearly, the more age-classes spared from being harvested (the higher is s), the longer it takes until the initial investment pays off. In fact, for $s \geq 11$, profits never reach the status-quo level. On the other hand, choosing $s \leq 7$ does, on average, not involve any short-term losses (but does not maximize NPV either, as suggested by the fact that profits stabilize at a lower level than when $s = 9$). The trade-off is also documented in the column "ttbe" of Table 1. Note that under most biological modeling assumption, the time to break even is very short — on the order of 2–3 years.

Figure 4 shows the development of biomass and harvest for the optimal selectivity ($s = 9$, solid line) and the current selectivity ($s = 3$, dotted line) when effort is chosen optimally under the baseline scenario of random recruitment. The two panels on the

Fig. 3. Development of instantaneous profits for different selectivities, baseline scenario.
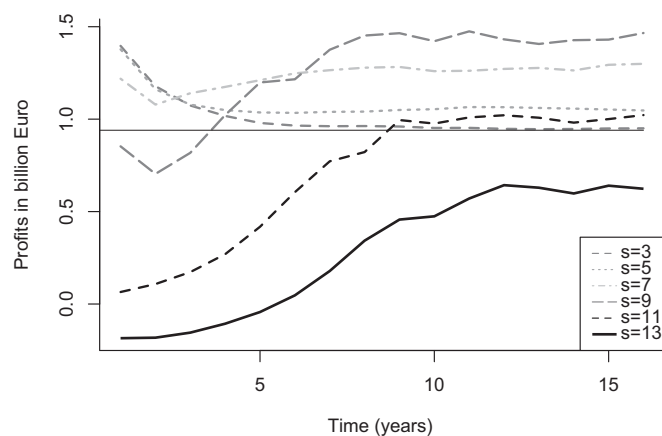

left plot the average paths. The two panels on the right side show one specific simulation to visualize the involved variability. The graphs highlight the formidable increase in the standing stock biomass due to improved management. Under both optimal and current selectivity, mean aggregate biomass is roughly 5.7 million tonnes (with fluctuations of up to 8.2 million tonnes). However, the stock composition between the two selectivity regimes is very different. This becomes clear when inspecting the harvest (the lower two panels of Fig. 4). The mean aggregate harvest under the best policy is twice as much as under the current selectivity regime (roughly 1 million tonnes, with fluctuations up to 2.2 million tonnes).[12]

Keep in mind that in the baseline scenario, there is no positive stock–recruitment feedback. When selectivity is fixed to its current level, the high biomass values that go along with maximizing

[11]Defined as ±1 standard deviation (SD) from the mean of profits in the latter 80 years of the time horizon.

[12]For comparison, the mean biomass over the last 20 years was 1.5 million tonnes (with a maximum of 2.4 million tonnes in 1993). The mean harvest was 500 thousand tonnes (with a maximum of 762 thousand tonnes in 1997). The highest biomass of the NEA cod stock since 1932 was 4.2 million tonnes (in 1946).

Fig. 4. Biomass and harvest under current (dotted lines) and optimal selectivity (solid lines).

Biomass, mean

Biomass, one simulation

Harvest, mean

Harvest, one simulation
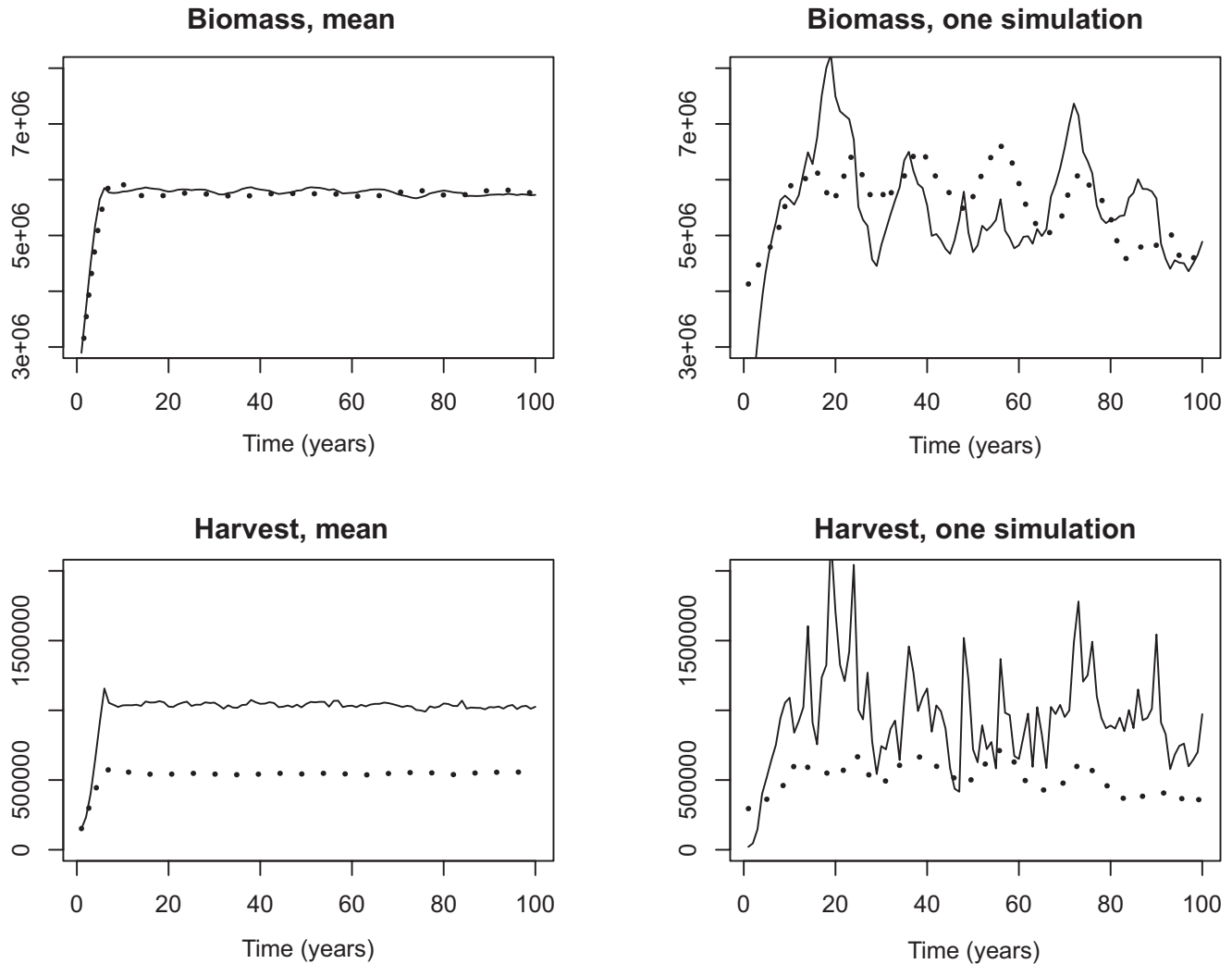
profits come solely from restraining effort. In contrast, a second tool is available when gear selectivity is also a control variable. As Beverton and Holt (1957) have pointed out, there is a trade-off between by increasing effort and postponing the first-age-at-capture. In fact, almost twice as much is harvested and profits are more than 40% higher under the optimal selectivity scenario, even though the mean total biomass is very similar whether $s = 3$ or $s = 9$.

Two points should be highlighted at this point: First, a postponing the first-age-at-capture leads to an increased variability in harvest and biomass. The reason is that the variability stemming from the random recruitment is exacerbated by the relative growth in biomass.[13] Second, concentrating harvest on older age-classes does not mean that there are less individuals of age 9 and above in the population. On the contrary, since fish do not die from fishing mortality during the first part of their life, there are more individuals that turn 9 in the first place, and also there are more individuals after harvesting. This is of course inconsequential for stock renewal when recruitment is modeled as random, but it plays a role when recruitment is endogenous.

Table 2. Economic sensitivity analysis, baseline case with e and s as control variables.

Parameter	Change	Policy	Effort	Select.	Biomass	Harvest	NPV
Cost	+10%	$e = 5.50\%x$	311	9	5660	1013	31.3
	−10%	$e = 5.68\%x$	318	9	5613	1017	33.1
Prices	$\boldsymbol{p} \times 1.5$	$e = 6.46\%x$	351	9	5428	1033	42.8
	$\boldsymbol{p} \times 0.75$	$e = 4.47\%x$	266	9	5947	975	21.8
Stock	$\beta_a + 0.03$	$e = 4.79\%x$	250	9	5228	1045	35.9
elasticity	$\beta_a - 0.03$	$e = 6.93\%x$	414	9	5982	978	27.5
Discount	$\delta = 0.91$	$e = 6.87\%x$	367	9	5349	1039	14.2
	$\delta = 0.98$	$e = 6.07\%x$	336	9	5534	1031	75.7

Note: $\boldsymbol{p}$, vector of age-specific prices; β_a, stock-output elasticity at age a; δ, discount rate. Other terms are as defined in Table 1; also see text.

Simulation results are insensitive to changes in economic parameters

An investigation of the sensitivity shows that the model results, in particular the optimal first-age-at-capture, are robust to reasonable changes in the empirically estimated economic parameters. Table 2 reports the simulation results for the

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[13]This is not an optical effect. The coefficient of variation for the harvest with constrained selectivity is 0.19 with a 95% confidence interval 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 $s = 9$.

baseline case when both effort *e* and selectivity *s* are control variables.

First, consider 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 leads to an increase 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 (Homans and Wilen 2005; Diekert et al. 2010*a*).

Second, consider the growth in value. Multiplying the vector of age-specific prices by 1.5 increases the NPV to €42.8 billion 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, but again the first-age-at-capture does not change.[14]

Another source of uncertainty is the estimation of the stock elasticities in the harvest function. I therefore increase and decrease all age-specific elasticity parameters by one standard error. 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, and again, the optimal selectivity does not change.

Finally, I change the discount rate. It is to be expected that this has a strong impact on the obtainable NPV. At a 2% discount rate, €1 in 100 years is worth 13 cents today, while at a 10% discount rate, €1 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. When the discount rate exceeds 18%, it is not optimal to spare start harvesting fish from the age of 8 instead of 9.

## Assessing efficiency gains under various biological scenarios

The assumptions about the underlying biological relationships have a strong impact on the obtainable profits. The introduction of a stock–recruitment relationship provides a second potential way of increasing harvest and profits, namely by allowing the spawning stock to reach a certain size. However, the form of the recruitment function, and in particular its asymptotic properties, also defines the upper bound for the stock size (see Fig. 5).

In the extreme case where the manager has full control over the recruitment by controlling the spawning stock, the optimal policy leads to an annual inflow of 1.4 million recruits to the fishery (in the baseline case, the fishery is supplied with roughly 600 thousand recruits on average). Hence, increasing the number of old fish (by avoiding the harvest of young fish) means that there are more valuable fish that can be caught, and even after harvesting there are more mature fish that contribute to the spawning stock. The combination of these two positive effects makes it especially worthwhile to choose gear selectivity, implying an additional gain of 54% (from €50.4 to €77.6 billion).

The same is true for the Beverton–Holt model. However, because the asymptotic value of the recruitment function is lower than the asymptotic value in the linear case, the NPV and the relative efficiency gains are lower than in the linear case (implying an additional gain of 49%, from €29.5 to €44 billion). The optimal first-age-at-capture is nevertheless still 9 years.

In contrast, when recruitment is governed by the Ricker function, an increased standing stock will, after a certain point, lead to decreasing recruitment. This has, of course, a strong impact on

Fig. 5. Spawning stock biomass and recruitment functions for domain of simulated values. Modeled recruitment functions: linear = dotted, Beverton–Holt = dashed, Ricker = solid.
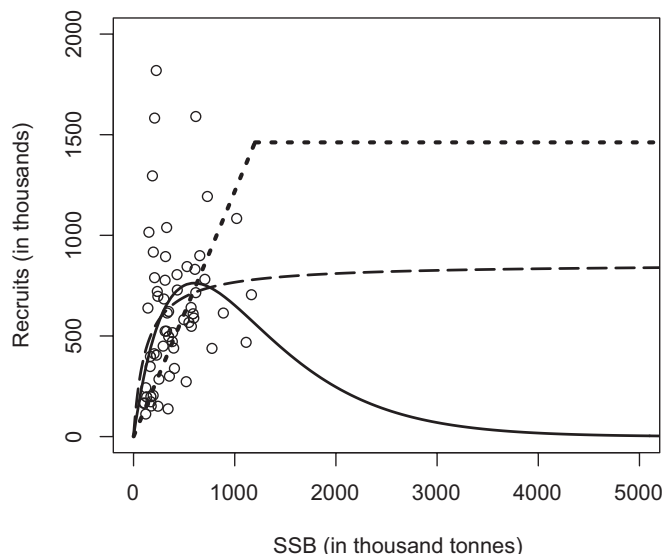

the estimate of efficiency gains. In fact, as the peak of the Ricker recruitment function is — by construction — within the range of observed stock levels, there is little room for improvement over the status quo. In spite of the relatively small scope for efficiency gains (roughly 12%), it is particularly important to be able to control selectivity in this model. As the penalty introduced by Ricker recruitment depends on the size of the spawning stock, not the overall stock size, it is of great value to separate the immature from the mature part of the stock and concentrate harvesting on the latter.

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. Here, a relatively small gear size could be optimal for two reasons. First, as the mass-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 to release pressure from the standing stock. By removing individuals from the population, the remaining individuals can grow at a higher rate. To isolate a possible "thinning" effect, I run additional simulations where mass-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 (as compared with €18 billion). Hence, a strategy of "thinning" the stock leads to higher profits under density-dependent growth.

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 because of the penalties for high stock sizes. Consequently, profits, harvest, and biomass remain

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[14]Recall that price is assumed to be independent of supply. While this is not unreasonable given that NEA cod is only a part of the global market for whitefish, this assumption may introduce an optimistic bias to the estimate of obtainable profits. The bias will be same for all simulations, though. (See also the discussion in Appendix A.)

Fig. 6. Comparison of obtainable NPV at first-age-at-capture.

(a) Baseline (b) BH (c) Ricker (d) ddw
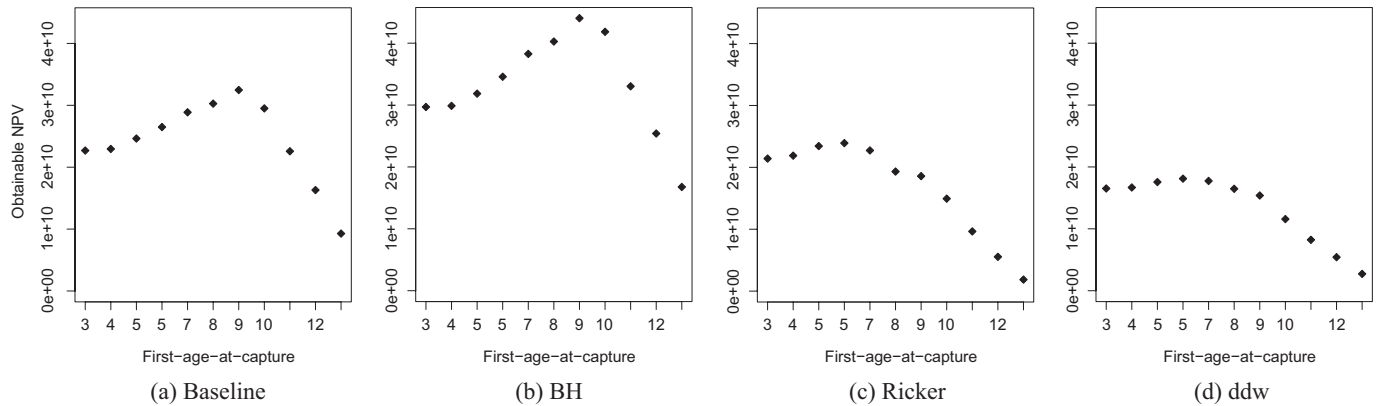
relatively low, and also the efficiency gains from choosing a larger mesh size are comparatively small.

Discussion

Figure 6, showing the NPV for the different values of first-age-at-capture, highlights the strong impact of modeling assumptions on the obtainable NPV and the most profitable policies. In particular, Ricker recruitment and density-dependent growth limit not only the overall biomass 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 the modeling approach is crude and likely to be a gross overstatement of the actual tendencies at work.

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 natural environment is close to the model with exogenous or Beverton–Holt recruitment and would not yet do any harm when the natural environment is close to the model with density-dependent masses or Ricker recruitment.

The simulations point to the potentially large implications of extrapolating model functions 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 asymptotic recruitment of zero (which is void of biological meaning). Still, this is a catch-22 situation, 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.

There are several limitations of this study that call for future work.

First of all, I consider the fishery of a species (cod) that has a relatively long life span and can reach large sizes, compared with many other species. As such it is a good model species for the current study, but it raises the question how far the results apply to other fisheries of other species. In fact, it is not so much the absolute number of age-classes or the terminal size that matters

Table 3. Biovalue (v) at age a for cod, saithe, and haddock.

	Age										
	3	4	5	6	7	8	9	10	11	12	13+
v_{cod}	1	1.78	4.02	5.37	7.23	8.36	10.92	12.04	11.3	10.61	9.54
v_{saithe}	1	1.16	1.41	1.86	1.97	2.3	2.24	2.24	2.03	1.78	1.7
$v_{haddock}$	1	1.43	1.71	4.32	4.25	—	—	—	—	—	—

for the existence of efficiency gains from improved selectivity (though it does of course determine the eventual size of these gains). The important aspect is that the individual fish grow distinguishably in mass and value with age. This description is arguably valid for many commercially harvested species, but there are also species for whose life histories the present model is not applicable without some modification. Pacific salmon, to take a stark example, are mainly caught just before they enter the rivers in which they spawn. Another example is the clam fisheries in the Northwest Atlantic, where the youngest age-classes are most valuable (Conrad 1982). Several other possible value–age combinations are discussed in Thunberg et al. (1998). Nonmonotonic value–age combinations would clearly lead to more complex specifications of the optimal selection policy that would need to be studied on a case-by-case basis. However, the main lesson from this work, the importance of acknowledging the structure of resource stock, would not be changed.

Moreover, the 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. 2010). Second, there is no such thing as a single-species fishery. Although the Barents Sea food web consist of rather few trophic levels, the interspecies interactions have an important effect on the stock dynamics (Hjermann et al. 2007). Moreover, as cod, saithe, and haddock are to some extent substitutable products, interspecies 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 the net. While doing justice to the economic and biological aspects involved with a multispecies system is beyond the scope of this study, I provide a first impression by considering Table 3, which gives the biovalue of a cohort of age-class a relative to age 3. Note that all values are given with respect to the corresponding age of cod.[15] Although

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[15]That is, the mass of a haddock in column "Age 4" is not the mass of a 4-year-old haddock, but the mass 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 (personal communication). Saithe grows in length at a similar speed as cod (Bergstad et al. 1987). Natural mortality is conventionally 0.2, similar to cod. Mass-at-age values for saithe and haddock are taken from ICES (2010, tables 4.6 and 5.3.3, respectively).

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 that corresponds to a first-age-of-capture for cod 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.

In this study, I have concentrated on profit as the manager's objective. In reality, fisheries management has to meet several criteria, such as stock stability, ecosystem resilience, but also issues such as employment and social equity. The discussion of the large variability implied by more selective harvesting (recall Fig. 4) showed that there might be trade-offs between the different objectives that a manager has to weigh. However additional concerns should not be added ad hoc, but rather modeled explicitly, for example, in the form of a viability analysis (Lara and Martinet 2009).

Last but not least, I have assumed that any policy can be accurately implemented. In reality, the managing authorities set the legal–administrative constraints while the actual harvesting is undertaken by individual fishers. Hence, it is imperative to wisely design regulations that are accepted and implemented by all stakeholders (Eikeset et al. 2011). A crucial aspect in this regard is to design the incentive structure so that fishers avoid to harvest small age-classes rather than discarding them. In a recent study, Feekings et al. (2013) show that discarding in the Danish cod fishery in the Baltic Sea has been very high (up to 40%). The discard ratio in the Danish fishery has, however, declined after incentives have been aligned by increasing the minimum legal landing size. In the Norwegian cod fishery of the Barents Sea, the policy to ban discards has shown to be very effective in inducing fishers to avoid harvesting small age-classes (Gullestad 2013).

To conclude, fisheries, as most renewable resources, involve both an important human and an important natural dimension. Their management should strive to take both factors into account, highlighting the need for interdisciplinary studies. Here, I have explored the effects of age-specific harvesting using the example of Northeast Arctic cod. In contrast with much of the previous literature, I explicitly account for the structural uncertainty surrounding the biological model and run the simulations under a large suite of different scenarios. Whether recruitment is exogenous or governed by a linear, a Ricker, or a Beverton–Holt function or whether growth is at its current mean 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 $s = 7$, simultaneously increasing profits and stock abundance. In light of the large potential gains from age-specific management, it is high time to move beyond traditional aggregate biomass reference points.

A final question remains. 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 2012). 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; Worm et al. 2009; Gutiérrez et al. 2011). Yet the numerous difficulties and challenges with solving collective action problems should not keep researchers from making suggestions to improve existing policies.

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Appendix A

Model calibration

The economic 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° latitude (Fiskeridirektoratet 1990–2005). One part of the data has previously been analyzed by Sandberg (2006) and Richter et al. (2011). It spans the years from 1990 to 2000. The other part of the data are newly acquired and are 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]

The share of cod in the total harvest for the sampled boats varies. I exclude all observations where cod is clearly undirected bycatch (i.e., cod makes up less than 2% of the harvest; 30 observations out of 864). Several candidates exist when selecting the best proxy for "effort". As it measures the intensity of fishing, it should include an element of the time that is spent harvesting (Gulland 1983). Moreover, if boat size is a major determinant of the harvesting process, size should be included in the effort proxy. Boat size could be captured by either length or tonnage. Here, the latter is chosen, as it correlates closer with harvest and costs. One unit of effort is therefore one unit of boat tonnage effectively catching cod for 1 day. (Note that with this definition, I implicitly assume a homogeneous fleet.) 48 observations have no information on tonnage, so I am left with a panel of 786 observations from 141 different boats over a period of 16 years (on average, 5.6 observations per boat, and some boats are observed in all years).

The basic form of the harvest function employed in this model is the so-called Cobb–Douglas function (eq. A.1). This form would, in principle, allow incorporation of a time trend (eq. A.2), as, for example, done by Sun (1998). Similarly, it can be derived as a specific case of a more general translog-production function (eq. A.3), as, for example, done by Hannesson (1983).

(A.1) $\qquad \log h_{i,t} = q + \alpha \log e_{i,t} + \beta \log x_t + \varepsilon_{i,t}$

(A.2) $\qquad \log h_{i,t} = q + \lambda t + \alpha \log e_{i,t} + \beta \log x_t + \varepsilon_{i,t}$

(A.3) $\qquad \log h_{i,t} = q + \lambda t + \alpha \log e_{i,t} + \beta \log x_t + \frac{1}{2}\gamma_{ee}(\log e_{i,t})^2$
$$+ \frac{1}{2}\gamma_{ex} \log e_{i,t} \log x_t + \frac{1}{2}\gamma_{xx}(\log x_t)^2 + \varepsilon_{i,t}$$

Table A1 shows estimated parameter values for these three functions. We observe three things. First, the coefficients α and β of the Cobb–Douglas function are significantly different from 1, rejecting the use of the standard Schaefer harvesting function.

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[16]The commodity price index for the industrial sectors from the Norwegian Bureau of Statistics was used.

[17]The employed exchange rate is 1 Euro = 8.1109 Norwegian kroner.

Table A1. Regression result for different aggregate harvest functions.

	Cobb–Douglas (eq. A.1)		Cobb–Douglas with time trend (eq. A.2)		Translog (eq. A.3)	
	Estimate	SE	Estimate	SE	Estimate	SE
λ			0.01	0.003	0.01	0.004
α	0.75	0.01	0.75	0.01	2.33	0.77
β	0.55	0.06	0.61	0.06	7.88	7.41
γ_{ee}					−0.08	0.007
γ_{ex}					0.01	0.05
γ_{xx}					−0.26	0.26
q	−9.63	0.9	−35.87	7.36	−91.54	48.79
$N = 786$	$R^2 = 0.81$		$R^2 = 0.81$		$R^2 = 0.83$	

Table A2. Regression result for age-specific harvest functions.

	Estimate	SE	z value	95% confidence interval
α	0.917	0.023	38.81	0.87, 0.96
β_3	0.733	0.049	14.91	0.67, 0.83
β_4	0.873	0.034	25.29	0.81, 0.94
β_5	0.931	0.027	33.77	0.88, 0.98
β_6	0.948	0.026	35.96	0.89, 1.00
β_7	0.955	0.026	35.93	0.90, 1.00
β_8	0.955	0.028	33.49	0.89, 1.01
β_9	0.946	0.032	29.31	0.88, 1.001
β_{10}	0.935	0.034	27.38	0.87, 1.00
β_{11}	0.921	0.045	20.49	0.83, 1.01
β_{12}	0.912	0.036	25.36	0.84, 0.98
β_{gp}	0.927	0.034	26.94	0.86, 0.99
q^*	−16.848	0.45	−37.46	−17.73, −15.97
$N = 786$		$R^2 = 0.89$		

This is well in line with previous studies.[18] Second, the time trend (as estimated by the parameter λ) is significant, but quite small. A slow rate of technological progress (here, I find 1% per year) has also been reported by Eggert and Tveterås (2013) (who found a rate of 0.8% per year). Technological progress, though present, does therefore not seem to be a major determinant of the harvesting process; variations in the resource stock are far more important. I thus choose to abstract from this aspect, also to keep the model free of additional parameters that distract from the main focus of the study. Third, the translog functional form does not entirely collapse to the Cobb–Douglas form (the coefficient γ_{ee} is significantly different from zero, while γ_{xx} and γ_{xe} are not). However, almost all other coefficients lose their significance, and as the translog functional form is considerably more cumbersome to work with in the simulations, I choose to model harvest by the Cobb–Douglas function. In some sense, this functional form can be viewed as a "minimum realistic model" of the production process.

The crux of estimating the parameters in the age-specific harvest function (eq. 3 in the main text) is that age-specific data are not available at the boat level. This means that it is not possible to estimate eq. 3 directly. I take the following approach to overcome this. 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 are 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 by using the share of each boat's harvest in total harvest, I am then able to calculate the individual age-specific harvest as $h_{a,j} = (h_a/h)h_j$.

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 overemphasize large-sample consistency for estimation efficiency. Moreover, I am interested in the harvest function of the population, not in the function for the boats in this specific sample. I obtain the parameters for eq. 3 in the main text by estimating eq. A.4 below (using the routine xtreg in the statistical program STATA; results are given in Table A2, robust standard errors are clustered at the year age level).

$$
\begin{aligned}
&\log h_{a,j,t} = q_j + \alpha \log e_{j,t} + D\beta_3 \log x_{3,t} + D\beta_4 \log x_{4,t} \\
\text{(A.4)} \quad &\qquad + \ldots + \varepsilon_{a,j,t} \\
&q_j \sim \mathrm{IID}(q^*, \sigma_q^2), \quad \varepsilon_{s,j,t} \sim \mathrm{IID}(0, \sigma^2), \quad \varepsilon_{a,j,t} \perp q_j \perp e_{j,t} \perp x_{a,t}
\end{aligned}
$$

where IID is independent and identically distributed.

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.[19]

Similar to effort above, I am only interested in the share of costs that is caused by catching cod. Therefore, the total cost is weighted by the boat-specific share of cod in the total harvest. With this definition, costs are linear by construction. (There are in fact no signs of nonlinearity in the data.) In spite of a constant marginal relationship between costs and effort, the marginal 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 A3.

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 kilogram. Prices at age (or more precisely, prices at mass) are in principle publicly obtainable from the Norwegian fishermen's sales organization.[20] However, this 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). I therefore take the mean values from 1997 to 2004 as a ballpark estimate of the vector of dock prices (see Table A4).

The biological model

Apart from the recruitment function, the parameters for natural mortality ϕ_a, for mass-at-age (w_a), and for the proportion of mature fish (mat$_a$) were inputs to the biological submodel. Values for the latter two parameters are taken to be the mean values

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[18] A value of $\beta = 1$ implies that the fish stock follows an ideal free distribution ($\beta = 1$; i.e. the density of fish declines at the same rate as the stock gets depleted). This is often argued to be an adequate description for demersal species. However, for NEA cod, Richter et al. (2011) 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 and 1978, finds values between 0.74 and 0.90.

[19] 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.

[20] Norges Råfiskelag; for the database see http://www.rafisklaget.no/portal/pls/portal/PORTAL.RPT_VAREPRIS_SLUTTSEDDEL.show_parms.

Table A3. Regression result for cost function (in year 2000 NOK).

	Estimate	SE	t value	Pr(>|t|)
Tonnage-days	63.4611	0.8368	75.84	<2e-16

Table A4. Price at age a.

	Age										
	3	4	5	6	7	8	9	10	11	12	13+
p_a (€·kg^{-1})	1.36	1.36	1.79	1.79	1.97	1.97	2.28	2.28	2.28	2.28	2.28

Table A5. Biological parameters.

	Age										
	3	4	5	6	7	8	9	10	11	12	13+
w_a (kg)	0.27	0.66	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

from 1990 to 2005, so that the biological and economic model are calibrated on the same time period (see Table A5). The data are from table 3.11, pp. 179, and table 3.12, pp. 182, in ICES (2010), respectively. I assume that all age-classes but the oldest face the same annual risk of dying from natural causes, so that the natural mortality is $\phi_a = 0.2$ for $a = 3, \ldots, A - 1$. 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) shows 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. The natural mortality of the oldest age-class is set to $\phi_A = 0.5$ to account for senescence.

Details on the numerical simulation procedure

The simulations were carried out in R, and the computer code is available as supplementary material[7] to this article. In this way, the interested reader could replicate my results[21] or adapt the model to different fisheries.

As mentioned in the main text, I explore a large set of (feedback) rules and policies from which I pick that combination of control variables that, on average, yields the highest NPV. By "rule" I 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. The grid of policies that are evaluated is consecutively narrowed until the mean NPV of the three best policies differs by less than 1 standard deviation.

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

(A) **fixed selectivity:** Set a fixed selectivity pattern, $s_t = s \in [3, 4, \ldots, A]$.
(B) **variable selectivity:** Select that age-class that 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 mass 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. For example, when $\theta = 1$, the age-class that is 1 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.[22]

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 ($e_{\max} = 500\,000$).

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 path will depend on the distribution of biomass over the different age-classes and may involve several periods of overshooting and undershooting (Tahvonen 2009). 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. 2011; the HCR is in effect similar to an escapement rule with a given target level). The escapement policies range from 400 000 tonnes to 14 million tonnes.

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 dynamic system that the best performing policies aim at. In particular, the best selectivity is — except in one case — the same.

Table A6 shows for Rules 1 to 4 the policy that maximizes the NPV (given in billion Euro) for the respective scenario. The values of the resulting mean effort, biomass, and harvest are given in units of thousands.

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) also leads to lower outcomes compared with both the

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[21]All estimated parameters are pasted into the code file except one set of VPA estimates, which is taken from the publicly available ICES report (ICES 2010).

[22]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. I 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. (2013).

Table A6. Overview of results, baseline model.

Rule	Scenario	Policy	Effort	Select.	Biomass	Harvest	NPV
1. HCR	Only e	$F = 0.22$	122	3	3600	672	22.6
	e and s	$F = 0.2$	221	8	5321	907	28.1
2. Fixed e	Only e	$e = 122$	122	3	4450	633	22.7
	e and s	$e = 284$	284	9	5391	1043	31.9
3. Feedback e	Only e	$e = 3.34\%x$	119	3	5673	537	22.7
	e and s	$e = 5.50\%x$	311	9	5656	1012	32.4
4. Escapement	Only e	$\bar{x} = 400\,000$	83	3	4585	612	21.1
	e and s	$\bar{x} = 500\,000$	308	9	5928	944	29.3

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 with the current policy target of $F = 0.4$, supporting the findings of Eikeset et al. (2013). The NPV increases by €2.9 billion from €19.7 to €22.6 billion, and also mean harvest increases only slightly (672 instead of 667 hundred thousand tonnes). However, there is a more pronounced increase of mean biomass (3.6 instead of 2.3 million tonnes).

The results under the variable selectivity rule are generally below the obtainable NPV from constant selectivity pattern, and I therefore do not report them in further detail. For completeness, the maximum obtainable NPV is €25.9 billion, again from Rule 3. Obviously, an adaptive selectivity pattern leads to less variable harvest.

Furthermore, I 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 becomes excessively high in times of low stock biomass.

Finally, by setting annual effort proportional to the overall stock biomass in a given year, I 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). I 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.

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