Incentives for Optimal Management of Age-Structured Fish Populations[☆]

Martin F. Quaas[a,*], Till Requate[a], Kirsten Ruckes[a], Anders Skonhoft[b], Niels Vestergaard[c], Rudi Voss[a]

[a] *Department of Economics, University of Kiel, Germany*
[b] *Department of Economics, NTNU, Trondheim, Norway*
[c] *Department of Environmental and Business Economics, University of Southern Denmark, Esbjerg, Denmark*

Abstract

We characterize optimal fishery management in an age-structured, bio-economic model where two age groups are harvested with costly and imperfect selectivity. We show that a system of tradable fishing permits, each allowing to harvest a specific number of fish that differs with age group, implements optimal age-structured harvesting, while traditional biomass quotas fail to solve the problem of growth overfishing. With our system, gear restrictions (such as mesh-size prescriptions) become obsolete. We apply our model to the Eastern Baltic cod fishery and quantify the benefits of optimal age-structured management.

Keywords: fishery management, growth overfishing, recruitment overfishing, optimal harvesting, age-structured model

JEL: Q22, Q57, Q28

[☆] This study was supported in part by the Future Ocean Excellence Cluster 80, funded by the German Federal and State Governments. We thank Dan Phaneuf and Quinn Weninger for helpful discussion and comments.

[*] Corresponding author: Department of Economics, University of Kiel, Wilhelm-Seelig-Platz 1, D-24118 Kiel, Germany. Phone: +49.431.880-3616, fax: +49.431.880-3150, email: quaas@economics.uni-kiel.de

1. Introduction

In all economic problems where market failure arises, economists typically ask two questions: first, what do efficient allocations look like, and second, how can these allocations be implemented through decentralized decision-making? This also applies to problems in the optimal management of fish stocks. The workhorse model for answering these questions is the biomass model (also known as lumped-parameter or surplus-production model), which describes the dynamics of a fish stock in terms of its biomass (Clark, 1990; Gordon, 1954; Scott, 1955). This model has often been criticized for oversimplifying biological structures and thus for generating inadequate management recommendations.[1] The crucial weakness of the biomass model is that it is incapable of distinguishing between two aspects of overfishing: recruitment overfishing and growth overfishing. Recruitment overfishing designates the problem of low reproduction because the spawning stock has been fished down. Growth overfishing, by contrast, means that fish are caught in an inefficiently low age and weight group. In order to address both forms of overfishing and hence formulate better management rules, it is necessary to look at the cohort (or age) structure of a given fish population.

In this paper we study how both problems, recruitment overfishing and growth overfishing, can be solved by means of market-based policy instruments. For this purpose, we set up a simple dynamic cohort model with four age groups: eggs and larvae, juveniles, young immature fish at non-spawning age, and mature fish at spawning age. Only the young immature and mature fish are subject to potential harvest. We consider selective fishing technology, which means that fishermen target the young and mature age groups, but we take into account both imperfect and costly selectivity. We use the concept of fishing technology in a broad sense: fishermen are free to choose different types of fishing gear as well as the time and location of harvest (Branch and Hilborn, 2008). Thus, fishermen's selective harvesting options are richer than the regulator's options for imposing selective harvesting by means of command-and-control.

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[1] Tahvonen (2009a, 2010) provides an overview of the criticism leveled at applying the biomass model in the economics of fisheries.

We characterize optimal harvesting and investigate how optimal management can be implemented by means of market-based policy instruments such as fees or tradable quotas.[2] We formally show that fixing the total allowable catch (TAC) and issuing tradable quotas measured in terms of *biomass* (an instrument currently used in many fisheries)[3] is bound to fail as a solution for the simultaneous problems posed by growth and recruitment overfishing.[4] This problem has been recognized before in the non-formal literature (e.g. Townsend, 1995) and may be one reason why, in most fisheries, tradable quotas are complemented by gear restrictions (such as minimum mesh-size) or minimum landing-size. In this paper, we focus on the design of economic instruments that can implement first-best, age-structured harvesting without gear restrictions.

We show that the first-best harvesting rule can be decentralized by issuing an appropriate number of tradable quotas, each allowing to harvest a specific number of fish that differs with age group. For the two harvestable age groups, this means that a permit allows to harvest either one mature fish or a fixed number of immature fish.

Furthermore, we show how a related price-based instrument in the form of harvesting fees can be used as an alternative policy. With these instruments, additional regulations in terms of gear restrictions (such as mesh-size prescriptions) or minimum landing-sizes become obsolete. Finally, to quantify both the total allowable catch and the quota price, we apply our model and analysis to the Eastern Baltic cod fishery.[5] For this fishery we

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[2] In accordance with our focus, we study how a system of tradable quotas could prevent growth overfishing. Since we do not study the effects of long-term use rights in fisheries, we refrain from using the term "individual transferable quotas (ITQs)" in this context.

[3] Individual quota systems in terms of biomass are used, for example, in Iceland, New Zealand, Greenland, and several member states of the European Union.

[4] This is in line with previous findings showing that undifferentiated biomass quotas will not implement efficient harvesting when there are production externalities (Boyce, 1992; Holland, 2011), or when the fish stock is heterogenous in space (Costello and Deacon, 2007). Diekert (2012) shows that this also holds for an age-structured fish stock when recruitment is exogenously given.

[5] To our knowledge, this is the first economic study on Eastern Baltic cod employing an age-structured optimization model. Previous studies on Baltic cod use biomass models to study the dynamics of open access (Kronbak, 2005), effects of trade liberalization (Nielsen, 2006), or investment in natural capital (Döring and Egelkraut, 2008); or consider age-structured models without optimization (Froese and

derive a cost function that accounts for age group selectivity based on mesh-size. Using this cost function, on the one hand, and biological recruitment data on the other, we are able to calculate optimal harvesting paths for both young and mature fish. Our results suggest that, under current practice, Baltic cod is significantly overfished despite a recent increase in stock numbers.

The number of bio-economic studies of age-structured fisheries is still rather small, although such models have been developed and analyzed since the 1970s (Hannesson, 1975; Reed, 1980; Getz and Haight, 1989; Clark, 1990). Recently, Tahvonen (2008, 2009a,b, 2010), Tahvonen et al. (2012), Diekert et al. (2010), and Skonhoft et al. (2012) derived both analytical and numerical results on optimal harvesting in a dynamic setting with age-structured fish stocks under various simplifying assumptions. Besides other issues, they study the effects of different types of gear selectivity, in particular knife-edge selectivity[6] (Beverton and Holt, 1957) and non-selective fishing gear. With the latter, where all age groups are harvested in fixed proportions, the optimal harvesting strategy may be "pulse-fishing," where all fish are harvested at certain points in time with no fishing in between (Hannesson, 1975; Tahvonen, 2010; Da Rocha et al., 2012). The present paper differs from these previous studies by considering a fishing technology in the broad sense referred to above, where the fishermen can select the age group harvested to some extent and where increasing selectivity is costly.

The paper is organized as follows: In the next section we present the model. In Section 3 we derive general results on the structure of optimal age-dependent harvesting rules, and in Section 4 we show how these can be implemented by means of economic instruments. We apply the model to the case of the Eastern Baltic cod fishery in Section 5. The final section concludes.

Quaas, 2011).

[6] Knife-edge selectivity means that all age groups above a certain age are subject to fishing mortality, while all younger and smaller fish escape.

2. The Model

2.1. Age-structured population model

In this section we set up a simple fishery model rich enough to analyze the harvesting of different age groups. The fish population at time (year) t is divided into four age groups: eggs and larvae X_{Et} (age < 1), juveniles X_{Jt} ($1 \leq$ age < 2), young immature fish X_{It} ($2 \leq$ age < 3), and mature fish X_{Mt} (age ≥ 3). All stocks, X_{jt}, $j \in \{E, J, I, M\}$, are measured in numbers of fish. Eggs and larvae (age group E) and juveniles (age group J) are assumed to be too small to be harvested. In principle, these two age groups could be lumped together into one group, but we keep them separate to avoid time lags of different lengths. Age group I consists of immature, non-spawning fish large enough to be of commercial value. Thus at an age of two years, the fish become vulnerable to fishing, i.e. they become recruits. Age group M, consisting of all mature fish of three years and older, represents the spawning stock. Aggregating all mature fish into one age group as the spawning stock is a simplification, as different age cohorts usually have different fecundity and mortality rates. For the purposes of this paper, however, this relatively simple model structure will suffice.

In a single time period (a year), four events occur in the following order: First, mature fish spawn, then fishermen harvest. In the third step, natural mortality further reduces the stocks of all groups, and finally somatic growth of individual fish takes place.

The reason for this order is as follows: As many fish species have short, well-defined spawning seasons, it is reasonable to consider spawning as a distinct event within the year. Without loss of generality, this event is the first within one period. We further assume that the fishing season is short enough to ignore natural mortality and growth during the fishing season.[7] Usually, natural mortality and somatic growth take place simultaneously throughout the year. However, as we are interested only in the surviving fish, assuming a sequential order of these processes involves no loss of generality.

To describe the population dynamics, we start with recruitment (the first event

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[7] Here we differ from Beverton and Holt (1957), where fishing is simultaneous with natural mortality and somatic growth, so that for fishing the optimal timing within a year may become an issue.

during a year). The stock of age group E (eggs and larvae) in year $t+1$ depends on the size of year t's spawning stock and is governed by a non-linear recruitment function $r(X_{Mt})$, with $r(0)=0$ and $r'(X_{Mt})>0$ for X_{Mt} sufficiently small. An example of such a non-linear recruitment function is the Ricker function that we employ in our case study (equation 11; Section 5).

In the second step, only age groups I and M are subject to fishing mortality. We use H_{It} and H_{Mt} to denote the harvesting quantities of age groups I and M. In the third step, all age groups are subject to natural mortality. Following the literature (Reed, 1980; Getz and Haight, 1989; Caswell, 2001; Tahvonen, 2009a), we assume that natural mortality rates and weights per individual fish may differ with age but are independent of population density. We use b_{ij} to denote the survival rates (net natural mortality) from age group i to age group j and w_j to denote the weight of an individual fish in age group $j=I,M$.

The equations of motion describing the dynamics of the age-structured fish population are then given by

$$X_{E,t+1} = r(X_{Mt}) \tag{1a}$$

$$X_{J,t+1} = b_{EJ}\, X_{Et} \tag{1b}$$

$$X_{I,t+1} = b_{JI}\, X_{Jt} \tag{1c}$$

$$X_{M,t+1} = b_{IM}\, (X_{It} - H_{It}) + b_{MM}\, (X_{Mt} - H_{Mt}) \tag{1d}$$

Note that both immature and mature fish that escape harvesting and that survive natural mortality will enter the next period's spawning stock $X_{M,t+1}$. We discuss this further in Section 6.

2.2. Harvesting technology, cost, and profit

As mentioned above, fishermen have several options in targeting a specific age group. For some species, selecting age groups can be done by choosing fishing grounds (Branch and Hilborn, 2008), as different cohorts can be found in different regions. Fishermen can also choose different types of fishing gear. Some passive gear types, such as traps, allow the selection of specific age groups with a comparatively high degree of precision

(Madsen, 2007). Last but not least, fishermen can select for older fish by increasing the mesh-size of fishing nets. In any case, selecting for age or size may be imperfect or costly.

Since in the most general setting harvesting costs depend on the catches and on the stocks of both age groups, we write the fishing fleet's aggregate harvesting cost function as $C(H_{It}, H_{Mt}, X_{It}, X_{Mt})$. We assume this cost function to have the following properties: Marginal harvesting costs of at least one targeted age group are positive, $C_{H_{jt}} > 0$, for $j = I$ or $j = M$. Usually, it will be the mature fish that are targeted, since these are typically more valuable than the immature ones. For the respective other age group $i \neq j$, there exists a level of harvest $\hat{H}_{it}$ such that $C_{H_{it}} > 0$ for $H_{it} > \hat{H}_{it}$ and $C_{H_{it}} < 0$ for $H_{it} < \hat{H}_{it}$. In other words, the harvesting cost for age group i has a minimum at $\hat{H}_{it}$ and increasing harvest of age group i beyond $\hat{H}_{it}$ induces positive marginal harvesting costs, while decreasing harvest of age group i below the level $\hat{H}_{it}$ creates negative marginal harvesting costs. We further assume that marginal costs for each age group will increase, i.e. $C_{H_{jt}H_{jt}} > 0$ for $j = I, M$, while marginal harvesting costs for one age group will decrease with the quantity of the other age group harvested, i.e. $C_{H_{It}H_{Mt}} = C_{H_{Mt}H_{It}} \leq 0$. This also means that increasing selectivity is costly.

We use this general cost function to derive results on policy instruments for implementing optimal management through decentralized decision-making (propositions in Section 4). For the case study in Section 5, we derive and parameterize a cost function for the Eastern Baltic cod trawling fleet (Appendices A.4 to A.7).

Annual profits are determined by the difference between total revenues from harvesting both age groups and total harvesting costs. Using p_j to denote the price per kilogram (assumed to be independent of the total harvest and fixed over time), profit in year t is given by $p_I\, w_I\, H_{It} + p_M\, w_M\, H_{Mt} - C\,(H_{It}, H_{Mt}, X_{It}, X_{Mt})$.

3. Optimal Harvesting

To characterize the optimal harvesting strategy, we consider a social planner determining optimal harvest levels for each age group. The planner's objective is to maximize the present value of annual profits discounted at a constant factor $\rho \in (0,1)$, given by

$$V = \sum_{t=0}^{\infty} \rho^t \Big(p_I w_I \, H_{It} + p_M w_M \, H_{Mt} - C\,(H_{It}, H_{Mt}, X_{It}, X_{Mt}) \Big) \tag{2}$$

subject to the population dynamics (1) together with the given initial numbers of fish in all four age groups X_{j0}, $j \in \{E, J, I, M\}$ and the constraint that harvest levels must be feasible, i.e. $0 \leq H_{jt} \leq X_{jt}$ for $j = I, M$. The Lagrangian function may be written as

$$\begin{aligned} L = \sum_{t=0}^{\infty} \rho^t \Big\{ & p_I \, w_I \, H_{It} + p_M \, w_M \, H_{Mt} - C\,(H_{It}, H_{Mt}, X_{It}, X_{Mt}) \\ & + \lambda_{Et} \, (r(X_{Mt}) - X_{E,t+1}) + \lambda_{Jt} \, (b_{EJ} \, X_{Et} - X_{J,t+1}) \\ & + \lambda_{It} \, (b_{JI} \, X_{Jt} - X_{I,t+1}) + \lambda_{Mt} \, (b_{IM} \, (X_{It} - H_{It}) + b_{MM} \, (X_{Mt} - H_{Mt}) - X_{M,t+1}) \\ & + \mu_{It} \, H_{It} + \mu_{Mt} \, H_{Mt} \Big\} \end{aligned} \tag{3}$$

where we use λ_{jt} ($j \in \{E, J, I, M\}$, $t = 0, \ldots, \infty$) and μ_{jt} ($j = I, M$ and $t = 0, \ldots, \infty$) to denote the Kuhn-Tucker multipliers (current-value shadow prices) of the population growth equations (1) and the multipliers of the lower boundaries of the feasible harvest levels (all in euros per fish), respectively.

Assuming positive stock sizes and suppressing the arguments of the cost function $C(H_{It}, H_{Mt}, X_{It}, X_{Mt})$, the first-order necessary conditions for optimal harvesting are given by

$$\frac{\partial L}{\partial H_{It}} = 0 \quad \Leftrightarrow \quad p_I \, w_I - C_{H_{It}} + \mu_{It} = b_{IM} \, \lambda_{Mt} \tag{4}$$

$$\mu_{It} \, H_{It} = 0$$

$$\frac{\partial L}{\partial H_{Mt}} = 0 \quad \Leftrightarrow \quad p_M \, w_M - C_{H_{Mt}} + \mu_{Mt} = b_{MM} \, \lambda_{Mt} \tag{5}$$

$$\mu_{Mt} \, H_{Mt} = 0$$

$$\frac{\partial L}{\partial X_{Et}} = 0 \quad \Leftrightarrow \quad \rho \, b_{EJ} \, \lambda_{Jt} = \lambda_{E,t-1} \tag{6}$$

$$\frac{\partial L}{\partial X_{Jt}} = 0 \quad \Leftrightarrow \quad \rho \, b_{JI} \, \lambda_{It} = \lambda_{J,t-1} \tag{7}$$

$$\frac{\partial L}{\partial X_{It}} = 0 \quad \Leftrightarrow \quad \rho \, (\lambda_{Mt} \, b_{IM} - C_{X_{It}}) = \lambda_{I,t-1} \tag{8}$$

$$\frac{\partial L}{\partial X_{Mt}} = 0 \quad \Leftrightarrow \quad \rho \, (\lambda_{Mt} \, b_{MM} - C_{X_{Mt}} + \lambda_{Et} \, r'(X_{Mt})) = \lambda_{M,t-1} \tag{9}$$

Conditions (4) and (5) require the marginal profit of harvesting immature and mature fish to equal the marginal opportunity cost of reducing the next period's spawning stock. They also imply that the Kuhn-Tucker multiplier μ_{It} is zero whenever immature fish are harvested and that the multiplier μ_{Mt} is zero whenever mature fish are harvested. Conditions (6) to (9) require the discounted future marginal values of fish stocks of all four age groups to be equal to their current value shadow prices.

The following proposition characterizes an interior solution with positive harvest of both age groups:[8]

Proposition 1. *An interior solution with positive harvest of both age groups is characterized by the condition*

$$p_M\, w_M - C_{H_{Mt}}(H_{It}, H_{Mt}, X_{It}, X_{Mt}) = \frac{b_{MM}}{b_{IM}}\left(p_I\, w_I - C_{H_{It}}(H_{It}, H_{Mt}, X_{It}, X_{Mt})\right) \tag{10}$$

where X_{jt} are the current stocks and H_{jt} are the optimal harvest levels of age groups $j = I, M$.

Proof. Condition (10) is obtained by dividing (4) by b_{IM} and (5) by b_{MM}, equating the resulting conditions, and using $\mu_{It} = \mu_{Mt} = 0$. □

Condition (10) states that for an interior optimal solution, the marginal profit of harvesting mature fish must equal the marginal profit of harvesting immature fish, weighted by the ratio of natural survival rates. The intuition for this result is as follows: For both age groups, optimal harvest is governed by the trade-off between the current benefit of immediate harvesting, on the one hand, and future benefits in terms of next period's harvest and increased recruitment on the other. The trade-off is different for the two age groups. An important reason why *current benefits* differ is that mature fish are usually much larger than young immature fish, and they often have a higher market price per kilogram. Thus, current revenues are greater for mature than for immature

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[8] Whether or not the optimal solution is an interior one with harvest of both age groups (i.e. $\mu_{It} = \mu_{Mt} = 0$) depends on the age-specific weights and survival probabilities, but also on the properties of the harvesting costs function. For the cost function (12) used in the case study on Baltic cod (Section 5) an interior solution is optimal whenever fishing takes place at all.

fish. *Future benefits* are similar for both age groups, as immature fish become mature and thus contribute to the next period's spawning stock, just as the surviving mature fish do. A currently immature fish that escapes harvesting increases the next period's spawning stock on average by b_{IM} individuals, whilst a mature fish that escapes will increase the next period's spawning stock on average by b_{MM} individuals. If these natural survival rates differ, different benefits accrue when allowing either immature or mature fish to escape. Note that (10) determines only the age composition of harvest, but not the absolute levels of harvest. Therefore this condition is independent of the discount rate.

As discussed before, the revenue per fish is typically much higher for mature fish. It thus follows from (10) that marginal harvesting costs must differ as well. It may even be the case that marginal harvesting costs are negative for one age group (usually the immature fish), so that optimal harvest quantities of immature and mature fish will differ in general. Accordingly, in implementing the optimal harvesting policy by setting TACs, different TACs would have to be used for the two age groups.

4. Decentralization through Market-based Policy Instruments

In this section we examine how optimal harvesting structures as characterized above can be decentralized by implementing market-based policy instruments such as harvesting fees and tradable harvesting quotas.[9]

4.1. Price-based regulation

In a setting of unregulated open access, fishermen will not take into account the marginal opportunity costs of harvesting either age group. This is because no benefits would accrue to them from leaving one extra fish in the sea. It is intuitive to suppose that two harvesting fees are necessary to achieve the first-best harvesting structure, one for the immature and another for the mature fish harvested. These fees would capture

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[9] In the literature on fisheries management, price-based instruments are sometimes referred to as landing fees. We prefer to use the term harvesting fees, as the source of market failure is not the landing but the harvesting.

the marginal opportunity costs of harvesting in terms of forgone future benefits from the stock of mature fish, i.e. the next period's harvest and increased recruitment. In the following proposition we show that the harvesting fees for the two age groups differ because age-specific survival rates differ. We use ϕ_{jt} to denote the harvesting fee for age group j in year t (in euros per fish).

Proposition 2. *Optimal harvesting of both age groups can be decentralized by setting two harvesting fees for immature and mature fish given by* $\phi_{It} = b_{IM}\,\lambda_{Mt}$ *and* $\phi_{Mt} = b_{MM}\,\lambda_{Mt}$*, respectively.*

Proof. For the proof see Appendix A.1. ☐

It is a special feature of this model with two harvestable age groups that the ratio of fees is always constant, even on the transitional path into the steady state, and given by the ratio of survival rates b_{IM} and b_{MM}. Note that this property does not generalize to the case of more than two harvestable age groups.

Decentralizing the optimal harvesting structure by fees is even simpler if the survival rates of immature and mature fish are identical. In this case, a single fee is sufficient to implement optimal harvesting of the two age groups. The assumption of equal survival rates for the different age groups is appropriate for several fisheries, including the Eastern Baltic cod fishery studied in Section 5. Formally, this result is a corollary to Proposition 2.

Corollary 1. *If* $b_{IM} = b_{MM}$*, optimal harvesting of both age groups can be decentralized by setting a single fee* $\phi_t = b_{IM}\,\lambda_{Mt} = b_{MM}\,\lambda_{Mt}$ *for the number of fish harvested.*

It is important to note that the optimal harvesting fees derived in Proposition 2 and Corollary 1 are related to the *number* of fish harvested, not to the weight or the biomass of the catch. The following argument shows that a conventional harvesting fee based on weight as in the biomass model would generate inadequate incentives for fishermen. Writing $\varphi_{jt} \equiv \phi_{jt}/w_j$ to denote the *optimal* fee per pound or kilogram of age group $j = I, M$ harvested, we see immediately from Proposition 2 that optimal "biomass" fees must fulfill the condition $(w_I/b_{IM})\,\varphi_{It} = (w_M/b_{MM})\,\varphi_{Mt}$. The *optimal* "biomass" fee is therefore larger for immature than for mature fish, i.e. $\varphi_{It} > \varphi_{Mt}$, whenever $w_I/b_{IM} < w_M/b_{MM}$. A *conventional* "biomass" fee, by contrast, applies to every kilogram of fish independently of age group and thus induces a distortion toward the over-harvesting of immature fish.

As discussed above, the inequality $w_I/b_{IM} < w_M/b_{MM}$ holds for most fish species, and for many of them the difference in optimal "biomass" fees for immature and mature fish will be large. For Baltic cod, for example, the optimal fee per kilogram of immature fish would be more than twice the optimal fee per kilogram of mature fish (see Section 5).

4.2. Quantity-based regulation

A harvesting quota is a permit (or license) to harvest a certain amount of fish. As discussed above, optimal harvesting can be implemented by setting two adequate caps (TACs) on the overall number of permits for each age group. In this setting, harvesting rights would be fully delineated according to age group, similar to the way how Costello and Deacon (2007) discuss harvesting quotas fully delineated in space.

An alternative approach is to set a single cap on the overall number of tradable permits, where one permit allows a fisherman to harvest either *one* mature fish or a number b_{IM}/b_{MM} of immature fish.[10]

Proposition 3. *Optimal harvesting of both age groups can be decentralized by issuing a total number of* $(b_{IM}/b_{MM})\,H_{It}+H_{Mt}$ *tradable permits permitting a fisherman to harvest either one mature fish or a number of* b_{IM}/b_{MM} *immature fish.*

Proof. See Appendix A.2. □

Note that with this system the regulator does not need to prescribe the allocation of quotas among the different age groups. The quota market allocates the harvests of immature and mature fish in optimal proportions. The driving forces that lead to this optimal allocation are the harvesting costs, which depend on the stock sizes of both age groups. If fishermen use the permits by targeting immature fish too heavily, the

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[10] This approach is reminiscent of the Montgomery (1972) concept of pollution licenses with exchange rates to account for the spatial dimension.

marginal harvesting costs of immature fish will rise (while the marginal harvesting costs of mature fish will decrease due to costly targeting), making it relatively less profitable to go for immature fish, and vice versa. In equilibrium, fishermen are indifferent between fishing one mature fish and a number of b_{IM}/b_{MM} immature fish.

If the survival rates of immature and mature fish are identical, optimal harvesting of the two age groups can even be implemented by issuing a total number of $H_{It} + H_{Mt}$ tradable permits allowing a fisherman to harvest either *one* mature fish or *one* immature fish. In this case, we may think of the total number of permits as a TAC on the overall number of fish harvested, combined with a system of tradable permits. This result is formally stated in the following corollary:

Corollary 2. *If $b_{IM} = b_{MM}$, then the optimal harvest of both age groups can be decentralized by setting a total allowable catch of size $H_{It} + H_{Mt}$ on the overall number of fish harvested and implementing it by means of tradable harvesting quotas in numbers.*

Proof. Follows directly from Proposition 3. ☐

Traditionally, quantity-based regulation of fisheries consists in a TAC/quota system in terms of biomass that does not take into account fish age. Such a system is bound to fail as a solution for the simultaneous problems posed by growth and recruitment overfishing, unless it is modified as follows: Optimal harvesting of both age groups could be decentralized by an appropriate overall number of "biomass" harvesting permits allowing a fisherman to harvest either one kilogram of mature fish or $(b_{IM}\, w_M/w_I)/b_{MM}$ kilograms of immature fish. This is because a fraction b_{IM} of currently immature fish that escape fishing would become mature, accompanied by an increase in weight by a factor of w_M/w_I, while a fraction b_{MM} of every kilogram of mature fish that escape fishing would remain in the spawning stock of mature fish. The "exchange rate" $(b_{IM}\, w_M/w_I)/b_{MM}$ between immature and mature fish will typically be much larger than one.

5. Application: Eastern Baltic Cod Fishery

The Eastern Baltic cod stock is historically the third-largest cod stock in the North Atlantic (Dickson and Brander, 1993). The cod is of considerable commercial importance for the region's fisheries. All countries bordering the Baltic Sea are involved in the cod fishery, and all of them except Russia are member states of the European Union (EU). Management decisions are settled in bilateral agreements between the EU and Russia. Between 1983 and 1992 a combination of high fishing pressure and low recruitment resulted in a decrease of spawning stock from over 600 million to about 52 million individuals (see Figure 1; ICES 2010). Landings from this fishery reached a peak of almost 400,000 tons in 1984 and then started to decline significantly, reaching a minimum of 45,000 tons in 1993 and remaining at low levels for a long time. Present estimates of stock biomass indicate that the SSB has recently increased. This is mainly due to the unusual strength of the 2005 and 2006 year classes (ICES, 2009) combined with more effective management of the Eastern Baltic cod fishery in recent years.

Current management measures are based on a formal recovery and management plan implemented since January 2008 with an overall target fishing-mortality level of 0.3 (Council of the European Union, 2007).[11] Besides the annual total allowable catch (TAC), which currently is set according to the target fishing mortality, the fishery is further managed by mesh-size regulations (minimum mesh size 110 mm), minimum landing sizes (38 cm), seasonal fishery restrictions, and area closures mainly designed to protect fish spawning in the three main deep basins of the Baltic Sea, i.e., the Bornholm Basin, the Gotland Basin, and the Gdansk Deep (ICES, 2009). The last two management instruments are not relevant to this study. The two instruments that aim at preventing growth overfishing are mesh-size regulations and minimum landing sizes. Table 2 in the appendix shows how these regulations have changed since the late 1980s. Regulations like these would become obsolete under type of management proposed here.

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[11] This figure corresponds to an instantaneous fishing mortality of 0.3 throughout the year, which implies a harvest of $1 - \exp(-0.3) = 26\%$ of the stock.

5.1. Data and calibration of the model

The parameterization of the population model for Eastern Baltic cod makes use of the best available biological data. Age-specific abundance data, the proportion of mature fish per age group, and natural mortality rates are based on assessment data using a stochastic multispecies model (SMS; ICES 2010). The weight of immature fish ($w_I = 0.21$ kg/individual) is estimated as the mean weight of two-year old cod in stock in the period 1974–2009, as reported by ICES (2010). The weight of mature fish ($w_M = 0.93$ kg/individual) is estimated as the mean weight of cod aged three years and older, weighted by relative age-group-specific abundance in 1974–2009 (data from ICES 2010). Note that lumping fish of three years and older into one age group is likely to underestimate the benefits of age-structured management for Eastern Baltic cod, as a further differentiation of the older age groups could increase welfare gains.

There is no need to calculate optimal stock numbers of eggs and juveniles. Accordingly, we estimate the stock-recruitment relationship $r(x_{Mt})$ between the number of mature and the number of immature cod (first quarter, lagged for two years) and set $b_{EJ} = b_{JI} = 1$. The two other survival rates, $b_{IM} = 0.81$ and $b_{MM} = 0.82$, are taken from the ICES (ICES, 2010) assessment report. For short-term forecasting, ICES standard stock assessment does not currently use any stock-recruitment function but rather a geometric mean of the years 1987–2005 (ICES, 2010). For our longer-term simulations, however, a stock-recruitment function is needed. We use the Ricker (1954) specification

$$r(X_{Mt}) = \gamma_1 \, X_{Mt} \, \exp(-\gamma_2 \, X_{Mt}) \tag{11}$$

which has a maximum at $X_M^{\text{peak}} = 1/\gamma_2$. This type of stock-recruitment relationship is an appropriate description of recruitment biology for Baltic cod, as there are clear indications of increased cannibalism at high stock numbers, mainly affecting juvenile fish. This phenomenon is due to higher spatial overlap between juvenile nursery grounds and an outspreading adult population when stock numbers are high. In order to find estimates for the two parameters γ_1 and γ_2, we use ICES (2010) data for the number of mature Eastern Baltic cod, X_{Mt}, and for the young immature recruits two years later, $X_{I,t+2}$, for the period 1974–2009. A non-linear, least-squares regression of (11), using the Levenberg-Marquardt least squares algorithm, yields the estimates $\gamma_1 = 1.59$ (standard error 0.34) and $\gamma_2 = 1.27 \cdot 10^{-3}$/million fish (standard error $0.57 \cdot 10^{-3}$/million fish). The peak value of $X_M^{\text{peak}} = 787$ million individuals is about 30% greater than the spawning stock observed in the early 1980s (approx. 600 million individuals).

At weights below one kilogram, both immature and mature cod come into the same size category, so we use $p_I = p_M$ in the simulation.[12] We assume that the price of cod will remain at the European reference price of $p_I = p_M = 1.095$ Euros per kg in 2010, which is the lowest price at which imports of cod into the European Union are allowed (Council of the European Union, 1999; European Commission, 2009).

Available effort and harvesting data do not allow for a direct estimate of the costs of selecting for age. For any of our attempts to directly estimate a cost function with a term that captures the costs of increasing selectivity (such as a cost function of the type specified in Singh and Weninger 2009), the corresponding parameters were insignificant.[13]

To derive a harvesting cost function for Baltic cod, we therefore use an indirect approach and consider only one option for selecting the age-group harvested, namely varying the mesh-size of trawl nets. Trawlers are the most common type of vessel catching cod in the Baltic sea (Kronbak, 2005). Furthermore, the Baltic cod trawling fishery is among the best-studied fisheries world wide with regard to size selectivity of fishing gear, and reliable data is available (Madsen, 2007). It should be kept in mind, however, that this approach tends to overstate the costs of selecting for age, as fishermen

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[12] According to European regulation (Council of the European Union, 1996), this is the category of 0.3–1 kg. In 2007, the ex-vessel price for cod in this size category was 12.63 Danish crowns (DKK) per kilogram (Fiskeridirektoratet, 2008). Overall, the price increases with weight. For the next higher size category of 1-2 kg., the price was 19.48 DKK/kg in 2007. As in practice some of the mature cod will come into this – or an even higher – size category, our assumption $p_I = p_M$ tends to relatively underestimate the value of mature cod harvested.

[13] A reason for this may be that, on the one hand, the Baltic cod fishery is regulated by minimum mesh-sizes (see Table 2), but on the other, fishermen have little incentive to mitigate bycatch of immature cod beyond that. Immature fish smaller than the minimum legal landing size is discarded. ICES (2010, Table 4.4.b) estimates the discard rates of immature cod to be between 14% in 1999 and 87% in 2007.

have several other options in selecting for age, including choice of the type of fishing gear and location of harvest (Branch and Hilborn, 2008).

For a given mesh-size, very small cod will escape almost completely while very large cod will be fully retained in the trawl net. In between these two extremes, the fraction of fish retained gradually increases with the length of the fish. The 'selection curve' of a typical trawl net is smooth and continuously increasing with the length of the fish. Fishery scientists commonly use logistic functions to describe the selection curves of towed gears (Wileman et al., 1996; Madsen, 2007) rather than a step function, as would be required for 'knife-edge' selectivity. Thus increasing the mesh-size reduces not only the fraction of (small) immature cod captured but also the fraction of (larger) mature fish captured. If the fisherman wants to maintain the same harvest of mature fish with less bycatch of immature fish, he has to increase overall fishing effort, which increases the harvesting costs. In other words, selectivity is costly.

In Appendix A.4 we derive the following harvesting cost function for the Baltic cod trawling fleet, assuming a generalized Gordon-Schaefer harvesting technology where the catchabilities of mature and immature cod depend on the mesh-size of the trawl net:

$$\begin{aligned} &C^{\text{trawl}}(H_{It}, H_{Mt}, X_{It}, X_{Mt}) \\ &\qquad = \frac{c}{1-\epsilon}\left[X_{Mt}^{1-\epsilon} - [X_{Mt} - H_{Mt}]^{1-\epsilon}\right] \cdot \left\{ 1 + \frac{\omega}{2}\,\frac{X_{Mt}^{1-\epsilon} - [X_{Mt} - H_{Mt}]^{1-\epsilon}}{X_{It}^{1-\epsilon} - [X_{It} - H_{It}]^{1-\epsilon}} \cdot \right. \\ &\left. \left[1 + \sqrt{1 + \frac{4}{\omega}\,\frac{X_{It}^{1-\epsilon} - [X_{It} - H_{It}]^{1-\epsilon}}{X_{Mt}^{1-\epsilon} - [X_{Mt} - H_{Mt}]^{1-\epsilon}} \left[1 - \frac{X_{It}^{1-\epsilon} - [X_{It} - H_{It}]^{1-\epsilon}}{X_{Mt}^{1-\epsilon} - [X_{Mt} - H_{Mt}]^{1-\epsilon}} \right]} \right] \right\} \end{aligned} \tag{12}$$

Here the parameter $\epsilon \in [0, 1]$ can be interpreted as the stock elasticity of harvest (sometimes also called the "schooling parameter"),[14] $c > 0$ is a cost parameter, measured in euros, and $\omega > 0$ is a dimensionless parameter that measures the costs of selecting for age, which are determined by the selectivity of the trawl net used (Madsen, 2007).

While the cost function (12) is not globally convex, it satisfies the assumptions stated

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[14] The lower limit $\epsilon = 0$ describes a fish stock with strong schooling behavior (Hannesson, 1983; Clark, 1990, chapter 7). In this case, harvesting costs depend only on harvests of both age groups and are independent of the initial stock. The upper limit $\epsilon = 1$ describes a highly dispersed fish stock. In

in Section 2.2 for the relevant domain where a significant effort is made to mitigate the bycatch of immature fish, such that the fishing mortality of immature fish is much smaller than that of mature fish (cf. Appendix A.4). Under the assumptions used to derive (12), marginal harvesting costs for immature fish are negative, or, put differently, reducing the harvest of immature fish generates abatement cost. Moreover, with the cost function (12) the harvesting costs become prohibitively high when the harvest of immature fish is zero. These properties reflect the issue referred to above, i.e. that the cost function (12) is likely to overstate the costs of selecting for mature fish.

In Appendix A.5 we calculate the value of the selectivity parameter $\omega = 0.017$ from (i) estimates (reviewed in Madsen 2007) of the selectivity of the most common trawl net used in the Baltic cod fishery (a trawl net with Bacoma escape window) and (ii) the length-at-age distributions of Baltic cod based on data from the Baltic International Trawl Survey. To derive parameter values for stock elasticity ϵ and the cost parameter c, we use historical data on stock numbers and harvests of mature and immature cod for 1974 to 2007 from ICES (2008) (see Figure 1), effort data, measured in days at sea, for the Danish fleet (period 1987–2007) from ICES (2008) and estimates of variable costs per day at sea from Kronbak (2005), updated with more recent data from Danish fishery accounts (1995–2007). For stock elasticity we arrive at the value $\epsilon = 1$ (see Appendix A.6), which is also supported by previous findings for cod fisheries (Hannesson, 2007; Kronbak, 2005). The resulting estimate for the cost parameter is $c = 72.9$ million euros with a standard error of 19.8 million euros (see Appendix A.7).

Table 1 summarizes the parameters used in the following simulation. In that table we also report the standard errors for the parameters estimated, i.e. γ_1, γ_2, and c. We use these standard errors for sensitivity analysis.

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this case, the cost function (12) is a generalization of the Spence (1974) harvesting cost function,

$$C(\cdot) = -c \ln\left[1 - \frac{H_{Mt}}{X_{Mt}}\right] \left\{ 1 + \frac{\omega}{2} \frac{\ln\left[1 - \frac{H_{Mt}}{X_{Mt}}\right]}{\ln\left[1 - \frac{H_{It}}{X_{It}}\right]} \left[1 + \sqrt{1 + \frac{4}{\omega} \frac{\ln\left[1 - \frac{H_{It}}{X_{It}}\right]}{\ln\left[1 - \frac{H_{Mt}}{X_{Mt}}\right]} \left[1 - \frac{\ln\left[1 - \frac{H_{It}}{X_{It}}\right]}{\ln\left[1 - \frac{H_{Mt}}{X_{Mt}}\right]} \right]} \right] \right\}.$$

Parameter	Symbol	Value	Standard error	Unit
Survival rate eggs/larvae–juveniles	b_{EJ}	1		
Survival rate juveniles–immature	b_{JI}	1		
Survival rate immature–mature	b_{IM}	0.81		
Survival rate mature–mature	b_{MM}	0.82		
Weight of immature	w_I	0.21		$\frac{\text{kg}}{\text{fish}}$
Weight of mature	w_M	0.93		$\frac{\text{kg}}{\text{fish}}$
Parameters of recruitment	γ_1	1.59	(0.34)	
function	γ_2	1270	(570)	$\frac{1}{\text{fish}}$
Ex-vessel price	$p_I = p_M$	1.095		$\frac{\text{euros}}{\text{kg}}$
Stock elasticity of harvest	ϵ	1		
Gear selectivity parameter	ω	0.017		
Cost parameter	c	72.9	(19.8)	million euros
Discount factor	ρ	0.95		

Table 1: Parameter values and standard errors (where applicable). Sources and methods are described in the text.

The optimization problem to be solved numerically then is to maximize (2),[15] with the specification (12) for the cost function, subject to the population dynamics (1) and given the initial stock numbers.

5.2. Optimization results

In optimal steady state, which is calculated by solving the first-order conditions for a steady state (see Appendix A.3), using the parameter estimates given in Table 1, the stock of mature (immature) cod consists of $X_M = 664$ ($X_I = 453$) million individuals, and the harvest amounts to $H_M = 275$ ($H_I = 26$) million individuals. The optimal stock of mature cod is thus about 10% higher than the maximum observed in the 1980s, while the optimal stock of immature cod is slightly below the maximum in the late 1970s. The average fishing mortality in steady state, $F = -\ln(1-(H_I+H_M)/(X_I+X_M)) = 0.316$, is close to the target fishing-mortality level proposed by the current management plan (Council of the European Union, 2007). The optimal steady-state harvesting fees are $b_{IM}\,\lambda_M = 0.68$ euros for an immature and $b_{MM}\,\lambda_M = 0.69$ euros for a mature cod.

In order to assess the uncertainty involved in calculating the optimal steady state, we compute 90% confidence intervals for the steady-state values employing a Monte-Carlo method. We assume independent normally distributed parameter values for the catchability coefficient η_0 and the cost/price ratio ζ with means and standard deviations according to the estimated values and standard errors reported in Table 1. For the parameters of the recruitment function γ_1 and γ_2 we assume bivariate normal distribution with means according to the estimated values reported in Table 1 and the variance-covariance matrix from the nonlinear least-squares regression. Drawing randomly from these distributions, we compute a large sample of steady-state values for different parameter sets and estimate the 90% confidence interval of steady-state values of the stock and escapement levels. The resulting 90% confidence intervals are $[367, 961]$ million individuals for the optimal steady-state stock of mature and $[288, 618]$ million individuals for immature cod. For optimal steady-state harvest levels, the corresponding

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[15] For the numerical optimization, we have chosen a finite time horizon long enough that a steady state was reached. In the following we report only the results for the first 25 years of transition dynamics.

90% confidence intervals are $[172, 378]$ million individuals for mature and $[18, 34]$ million individuals for immature cod. The confidence intervals for the optimal steady-state harvesting fees are $[0.56, 0.82]$ euros for a mature cod and $[0.55, 0.81]$ for an immature cod.[16] These figures show that the optimal steady-state values are subject to considerable uncertainty, especially with regard to the upper bounds on steady-state spawning stock and escapement. This reflects the general uncertainty associated with biological stock assessment, which is amplified by the uncertainties in the economic parameters used to calculate the optimal steady state. Nevertheless, the results of the sensitivity analysis indicate that Baltic cod is significantly overfished despite the recent increase in spawning stock numbers. The lower bound of the 90% confidence interval for the optimal steady-state level of the stock of mature cod (367 million individuals) is 23% above the value of 2008, when the spawning stock was 298 million individuals (ICES, 2010).

For dynamic optimization we use the reference set of parameter values reported in Table 1.[17] The optimization starts in 2006, because stock assessment data contain stock numbers only for age groups of two years and older, and because the newest data from SMS stock assessments is available for 2008 (ICES, 2010). To obtain initial stock numbers for all age groups in our model, we use the number of immature cod from 2008 (or 2007, respectively) as the number of eggs/larvae (juveniles) for 2006, assuming zero natural mortality for the two youngest age-groups in our model.

The resulting optimal developments of the stock and harvest of mature Eastern Baltic cod are shown in Figure 1 A, the optimal developments of the stock and harvest of immature cod in Figure 1 B. According to the results, it is optimal to stop harvesting

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[16] Uncertainty in the discount rate was not included in this sensitivity analysis, because the discount rate was not derived from an empirical estimation. If we lower the discount rate to 1% per year, using the mean estimates for all other parameters, the steady-state values are $X_M = 699$, $H_M = 273$, $X_I = 456$, and $H_I = 23$ million individuals. If we increase the discount rate to 10% per year, the steady-state values are $X_M = 618$, $H_M = 275$, $X_I = 447$, and $H_I = 31$ million individuals.

[17] For the numerical calculation we employ the interior-point algorithm of the Knitro (version 6.0) optimization software with Matlab (Byrd et al., 1999, 2006).

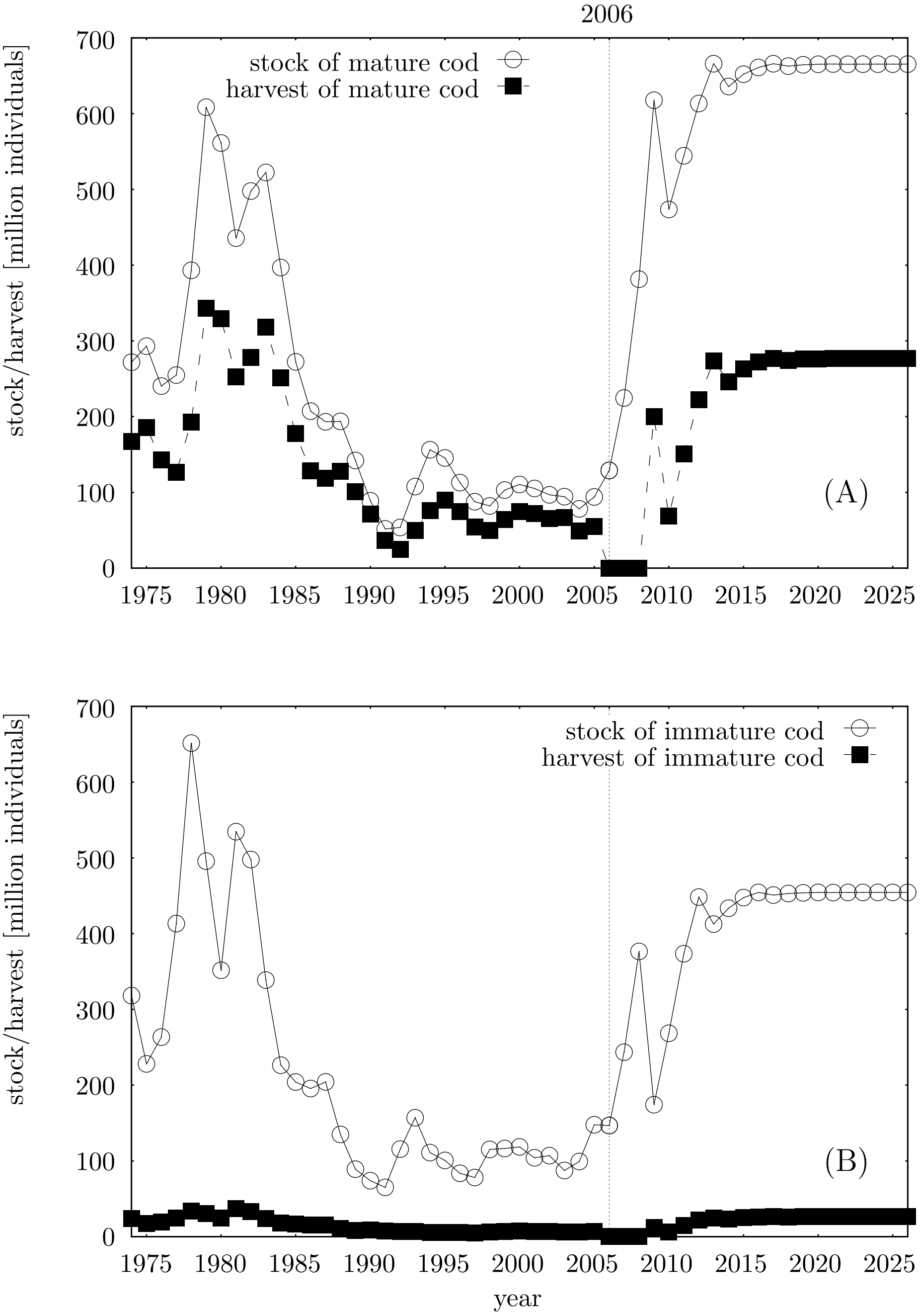

Figure 1: Stocks and harvests of mature (A) and immature (B) Eastern Baltic cod. ICES data from 1974–2006, results of numerical optimization from 2007 to 2030. Parameter values are given in Table 1.

for three years. After a period of zero harvesting, the steady state is approached in damped oscillations with a period of "over-shooting" when the stock of mature cod exceeds the steady-state value. The reason is the very strong year class of eggs/larvae in 2006, which we use as initial condition for the numerical optimization.[18]

The most rapid approach to constant escapement (i.e. the number of fish remaining in the stock after harvesting), which would be optimal in the corresponding biomass model (both in continuous and discrete time Clark 1990; Reed 1979), is not optimal in the age-structured setting considered here. This result is similar to a model with multi-species interactions, where again the most rapid approach is generally not the optimal solution (Clark 1990, chapter 10). Also previous studies on age-structured fisheries find optimal solutions that differ from the constant-escapement solution (e.g. Hannesson, 1975; Tahvonen, 2010). The intuition is that the time-lagged structure of the age-structured population model (1) includes effects of current escapement levels on the stock sizes up to three periods ahead in time. Depending on the initial age structure of the population, the same (constant) level of escapement would not be the optimal policy in the transition to the steady state.

The Eastern Baltic cod fishery has been subject to various regulations aimed at preventing growth overfishing for decades (Table 2 in the appendix). Although these regulations involve high transaction costs for monitoring and enforcement, the results shown in Figure 1 B indicate that they have been effective in reducing the harvest of immature cod to levels that are similar to the optimal levels resulting from our calculation. Overall, however, the management has been largely inefficient for a long time, as the clearly sub-optimal stock sizes of mature cod show.

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[18] Osciallations along the optimal path might also occur due to the non-monotonicity of the stock-recruitment function (11). We can exclude this explanation here, however, as the optimal spawning stock is always below the peak of the Ricker function (787 million individuals). Note also that the dynamic optimization using Knitro leads to the same steady-state values as obtained by solving the first-order conditions (see above).

5.3. Optimal and second-best regulation

We now turn to the characterization of optimal regulation, focusing on the price-based instruments characterized in Proposition 2, and study two second-best scenarios: management by a biomass fee or by a fee on the number of fish, both without differentiating for age.

Panel (A) in Figure 2 shows the time paths for the optimal harvesting fees for mature and immature cod. For the transition period of three years, the optimal harvesting fee already exceeds the profit per unit of harvest of mature cod at the beginning of the season, where harvesting costs are at a minimum, so that no fisherman would have an incentive to start fishing. Accordingly, profits are zero during these three years. After the transition period, the harvesting fee and the current profit at the end of the fishing season coincide (cf. Condition 5).[19] Overall, the harvesting fee is substantial, with steady-state values of almost two thirds of the ex-vessel price of landed fish.

Under optimal management, annual profits of the fishery increase to a steady-state value of about 231 million euros per year. The present value of profits over the period 2006-2026 is 2.047 billion euros (at an interest rate of 5%, i.e. with the discount factor $\rho = 0.95$ used in the simulations). This is a substantial figure given that in the past the Eastern Baltic cod fishery was under conditions close to open-access, with hardly any profits (Kronbak, 2005).

To illustrate the benefit of optimal management, we compare the optimal outcome with the second-best optimal outcome under a pure biomass fee. Under a fee τ_t on harvest measured in terms of biomass, the representative fisherman chooses harvest numbers of immature H_{It} and mature fish H_{Mt} in each period to maximize profits, $(p_I - \tau_t)\, w_I\, H_{It} + (p_M - \tau_t)\, w_M\, H_{Mt} - C(H_{It}, H_{Mt}, X_{It}, X_{Mt})$. Given the resulting harvest numbers as functions of the current biomass fee τ_t, the second-best optimal time path of biomass fees maximizes the objective function (2) subject to population dynamics (1). Panel (B) in Figure 2 shows the time path of the second-best optimal biomass fee; the

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[19] In this period with positive optimal TAC, the price for tradable quotas would be equal to the optimal harvesting fee.

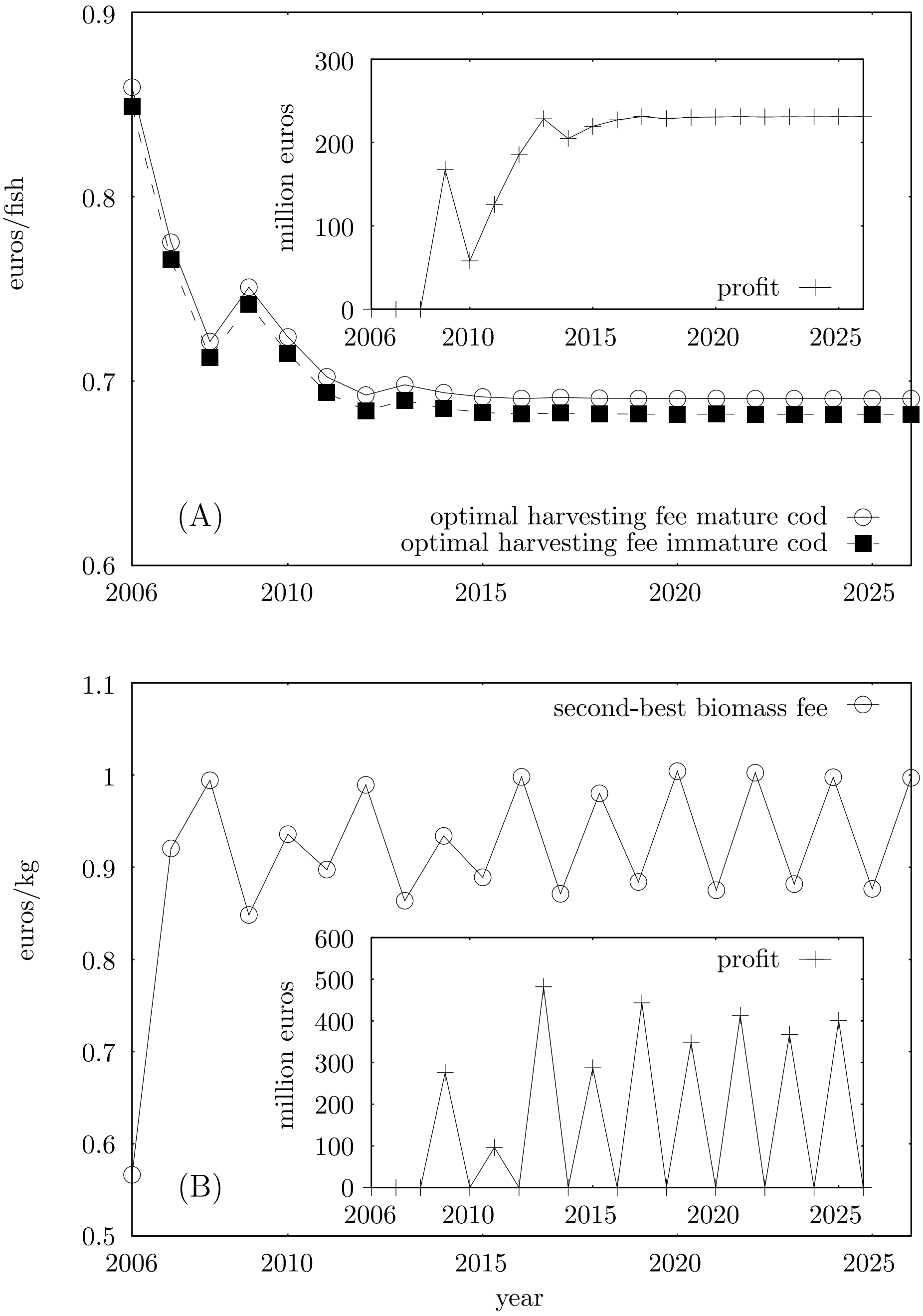

Figure 2: Panel (A): optimal harvesting fees for mature and immature cod, and current profits. Panel (B): second-best harvesting fees in terms of biomass, and current profits, for linear and nonlinear objective function. Parameter values are given in Table 1.

figure in the box shows the time path of current profits.[20] The second-best optimal biomass fee induces a pulse-fishing solution: After a transitional period of three years, where the fee is set prohibitively high so that no fishing takes place, only every second year the fee is sufficiently low to render fishing profitable. The intuition for this result is that a pure biomass fee has a similar effect as non-selective fishing gear, as the fisherman have little incentive to select for age. As age selection is not implementable, pulse-fishing is the best choice for the fishery manager (Hannesson, 1975; Tahvonen, 2010).

The welfare gain of optimal management compared to a pure biomass fee amounts to 291 million euros (2.047 billion euros under optimal management vs. 1.756 billion euros under a pure biomass fee).

Another second-best scenario consists in setting a single harvesting fee on the number of fish, without differentiating for age. The resulting time paths for this scenario are quite similar to the optimal outcome and therefore omitted. This is because the survival rates for immature and mature cod are quite similar, and thus the first-best harvesting fees in terms of numbers are not very different for the two age groups (cf. Figure 2(A)). Under the second-best scenario of a single fee in terms of numbers, the present value of profits from the Baltic cod fishery is only slightly smaller than the optimal value and amounts to 2.042 billion euros over the period 2006–2026.

Finally, the optimal management can be compared to the value of the fishery under the current recovery and management plan.[21] To compute this value, we fix the annual fishing mortality at 0.26 (see footnote 11) and assume that the age composition of the catch corresponds to its average value in the period 1995–2005. This means we set the fishing mortality of immature cod at 9% of the fishing mortality of mature cod (cf. Figure 1). The resulting net present value of profits over the period 2006–2026 is 1.631 billion euros, which is a considerable improvement over the past situation of the Baltic cod fishery, but clearly below the optimum with a present value of 2.047 billion euros over the period 2006–2026.

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[20] For this sake, we numerically solve the representative fisherman's optimization problem and use Knitro with Matlab to determine the second-best optimal time path of the biomass fee.

[21] We thank a reviewer for pointing this out.

6. Discussion and Conclusion

In this paper we analyze an age-structured fishery model enabling us to distinguish spawning stock and non-spawning stock and to address the problems of recruitment overfishing and growth overfishing. We have seen that apart from special cases immature fish and mature fish should be harvested in different quantities.

Our study has important policy implications. First, the type of quota management currently implemented in most fisheries fails to solve the problem of growth overfishing, as quotas are expressed in terms of biomass independent of age. Second, optimal age-structured management can be implemented by means of suitable market-based policy instruments. We have shown that setting age-specific harvesting fees can solve the problems of growth and recruitment overfishing simultaneously. If natural survival rates of the two age groups subject to harvesting are identical a single harvesting fee will suffice to decentralize the first-best harvesting rule.

Alternatively, optimal harvesting can be decentralized by issuing tradable quotas, each allowing to harvest a specific number of fish that differs with age group. Under such a policy one permit allows to harvest either one mature fish or a certain number of immature fish, which is determined by the ratio of natural survival rates. The quota market will then efficiently allocate the TAC among the different age groups. One notable aspect of this result is that the quota market will thereby bring about an optimal age structure in the fish stock. This is an important difference from the conclusion drawn from the "biomass" model, where the ecological effectiveness of management is guaranteed by setting the appropriate TAC, irrespective of whether quotas are tradable or not.

We have assumed that there are only two harvestable age groups and that surviving immature and mature fish contribute equally to the next periods spawning stock. When extending the analysis to more age groups, the optimal harvesting fee, or the exchange rates for harvesting permits, would have to be more differentiated according to the number of age groups subject to harvesting. Furthermore, when taking into account different fertilities of different age groups, the ratio(s) of optimal harvesting fees, or exchange rates for harvesting permits, would also depend on parameters other than the natural survival rates (e.g. fecundity rates) and may change over time during the transition phase to a steady state.

Implementing a regulation based on numbers of fish rather than on biomass should not be too difficult in practice. Grouping the catch into different sizes is common practice, as different sizes of fish fetch different prices at auctions. It is easy to estimate the number of fish in a specific size group with reasonable precision. The estimation could be improved if the size groups for marketing, which are currently set somewhat arbitrarily (for example by the Council of the European Union, 1996), were adjusted accordingly.

With a regulation as proposed here, fishermen may try to highgrade their catch by discarding immature fish. This raises concerns about potential management problems and transaction costs associated with costly monitoring and enforcement. These concerns apply here in the same way as to other fisheries where bycatch is an issue (Jensen and Vestergaard, 2002; Singh and Weninger, 2009). For the case of the Baltic cod fishery on-board observers or camera-based systems are likely be introduced in the future anyway, as the current reform of the Europan Common Fisheries Policy proposes a complete ban on discards (European Commission, 2011). Under such conditions, the proposed regulation could be introduced at little additional costs. In other fisheries, however, monitoring and enforcing a direct gear regulation might come at less transaction costs than full monitoring of catches.

Practical implementation of fishery management requires quantifying the TACs or, with the price-based approach, quantifying the corresponding harvesting fees for the different age groups. As an illustration, we have applied our age-structured model to the Eastern Baltic cod fishery. For both age groups we compute the time paths for total allowable catch that maximize the present value of resource rents. It involves zero harvesting for a period of three years. Then the steady state is approached in damped oscillations with a period of "over-shooting" when the stock of mature cod exceeds the steady-state value and ultimately a yearly harvest substantially higher than current harvests ensues.

A comprehensive sensitivity analysis shows that despite a recent increase the current

Baltic cod stock is significantly smaller than the optimal steady-state stock. However, the sensitivity analysis also shows that the quantification of optimal TACs is subject to considerable uncertainty. One conceivable source of uncertainty may result from interaction with other species, which we do not model here. For example, Baltic cod feeds on sprat and herring, while sprats feed on cod eggs and larvae (Köster and Möllmann, 2000). Further research should therefore try to integrate species interaction into age-structured models to reduce the uncertainties and to allow for the development of an integrated policy regulating several commercial species simultaneously.

Appendix

A.1. Proof of Proposition 2

For $\mu_{It} = \mu_{Mt} = 0$ and targeting both age groups, the result follows immediately from Conditions (4) and (5). (The spawning stock's shadow price λ_{Mt} is determined by Conditions (4)–(9) for optimal harvesting.) For $\mu_{It} > 0$ and $\mu_{Mt} = 0$, we have $p_I\, w_I - C_{H_{It}}(H_{It}, H_{Mt}, X_{It}, X_{Mt}) < \phi_{It}$. As $C_{H_{It}H_{Mt}} < 0$, this holds for all stocks of mature fish between $(X_{Mt} - H_{Mt})$ and X_{Mt} and hence over the whole harvesting period. For individual fishermen it will not be optimal to target immature fish at all, which is the socially optimal solution. The case $\mu_{Mt} > 0$ and $\mu_{It} = 0$ is analogous.

A.2. Proof of Proposition 3

In this appendix we use ψ_t to denote the permit price. The representative fisherman's static profit maximization problem is

$$\max_{H_{It}, H_{Mt}} \left(p_I\, w_I\, H_{It} + p_M\, w_M\, H_{Mt} - C(H_{It}, H_{Mt}, X_{It}, X_{Mt}) - \psi_t \left(H_{Mt} + \frac{b_{MM}}{b_{IM}}\, H_{It} \right) \right), \tag{13}$$

as b_{MM}/b_{IM} quotas are needed to catch one immature fish. From profit maximization of fishing firms we have $p_M\, w_M - C_{H_{Mt}} = \psi_t$ if age group M is harvested in equilibrium, and $p_I\, w_I - C_{H_{It}} = (b_{MM}/b_{IM})\, \psi_t$ if age group I is harvested in equilibrium. If, on the other hand, $p_M\, w_M - C_{H_{Mt}} < \psi_t$, mature fish will not be harvested, and if $p_I\, w_I - C_{H_{It}} < (b_{MM}/b_{IM})\, \psi_t$, immature fish will not be harvested.

If both age groups are harvested, a market equilibrium implies

$$\frac{p_M\, w_M - C_{H_{Mt}}}{b_{MM}} = \frac{p_I\, w_I - C_{H_{It}}}{b_{IM}} \tag{14}$$

This is the condition for the optimal harvesting of both age groups given in Proposition 1. As furthermore the total number of permits is $(b_{IM}/b_{MM})\, H_{It} + H_{Mt}$, comparison with the first-order conditions for optimal management, (4) and (5), implies a quota price of $\psi_t = b_{MM}\, \lambda_t$, i.e. the permit market leads to optimal harvesting.

If zero harvesting of immature fish is optimal, the total number of permits is H_{Mt}. For mature fish the market equilibrium condition is $p_M\, w_M - C_{H_{Mt}} = \psi_t$. If all permits are used to harvest mature fish, i.e. $H_{It} = 0$, we have $p_I\, w_I - C_{H_{It}} < (b_{MM}/b_{IM})\, \psi_t = (b_{MM}/b_{IM})\, (p_M\, w_M - C_{H_{Mt}})$. The left-hand side of this inequality monotonically increases with the harvest of mature fish,

$$\frac{d\,(p_I\, w_I - C_{H_{It}})}{dH_{Mt}} = -C_{H_{It}H_{Mt}} > 0 \tag{15}$$

Thus immature fish will not be harvested at all. Comparison of the market-equilibrium condition $p_M\, w_M - C_{H_{Mt}} = \psi_t$ with the first-order conditions for optimal management, (4) and (5), implies a quota price of $\psi_t = b_{MM}\, \lambda_t$, i.e. the permit market also leads to optimal harvesting when zero harvesting of immature is optimal. The final case with zero harvesting of mature fish is analogous.

A.3. Steady-state conditions

In a steady state, all stocks, harvests, and current-value shadow prices are constant, i.e. $X_{j,t+1} = X_{jt} = X_j$, $H_{j,t+1} = H_{jt} = H_j$, and $\lambda_{j,t+1} = \lambda_{jt} = \lambda_j$ for $j \in \{E, J, I, M\}$. From the population dynamics (1), we obtain the following two steady-state conditions:

$$X_I = b_{JI}\, b_{EJ}\, r(X_M) \tag{16a}$$

$$X_M = b_{IM}\, (X_I - H_I) + b_{MM}\, (X_M - H_M) \tag{16b}$$

Using the optimal control conditions (4–9), we obtain the following steady-state conditions for an interior optimal steady state:

$$p_I\, w_I - C_{H_I} = b_{IM}\, \lambda_M \tag{17}$$

$$p_M\, w_M - C_{H_M} = b_{MM}\, \lambda_M \tag{18}$$

$$\rho\, \left(\lambda_M\, b_{MM} - C_{X_M}\right) + \rho^4\, b_{EJ}\, b_{JI}\, \left(\lambda_M\, b_{IM} - C_{X_I}\right)\, r'(X_M) = \lambda_M \tag{19}$$

A.4. Derivation of cost function (12)

We assume that within a fishing period, a continuum of fishermen $\tau \in [0,1]$ is harvesting sequentially. Instantaneous harvest flows $h_{It}(\tau)$ and $h_{Mt}(\tau)$ are determined by fishing effort $e_t(\tau)$ of fisherman τ as follows:

$$h_{It}(\tau) = \eta_I\, e_t(\tau)\, x_{It}(\tau)^{\epsilon} \tag{20a}$$

$$h_{Mt}(\tau) = \eta_M\, e_t(\tau)\, x_{Mt}(\tau)^{\epsilon} \tag{20b}$$

Here we use $x_{jt}(\tau)$ to denote the stock of age $j = I, M$ left in the sea when fisherman τ starts fishing, so that $x_{jt}(0) = X_{jt}$ at the beginning of year t's fishing season and $x_{jt}(1) = (X_{jt} - H_{jt})$ at the end, where $H_{jt} = \int_0^1 h_{jt}(\tau) d\tau$. Moreover, we use ϵ to denote the stock elasticity of harvest and the parameters η_I and η_M to denote the catchability coefficients of both age groups. Integrating Equations (20a) and (20b) (see also Clark 1990, p. 203), we arrive at

$$\eta_I\, E_t = \frac{1}{1-\epsilon}\, \left(X_{It}^{1-\epsilon} - (X_{It} - H_{It})^{1-\epsilon}\right) \tag{21a}$$

$$\eta_M\, E_t = \frac{1}{1-\epsilon}\, \left(X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}\right), \tag{21b}$$

where E_t denotes aggregate fishing effort in period t. We further assume that catchabilities of both targeted and bycaught age groups can be influenced by choosing the variable m_t. Here we interpret this variable as the mesh-size of the trawl net. Following the literature (Wileman et al., 1996; Madsen, 2007), we assume that the catchabilities depend on mesh size m_t as follows

$$\eta_I(m_t) = \eta_0\, \left(1 + \exp\left(\frac{m_t - \beta_I}{\alpha_I}\right)\right)^{-1} \tag{22a}$$

$$\eta_M(m_t) = \eta_0\, \left(1 + \exp\left(\frac{m_t - \beta_M}{\alpha_M}\right)\right)^{-1}. \tag{22b}$$

The first factor in both equations is the probability η_0 that a fish will enter the trawl net. Here we assume that this probability is equal for both age groups, which means that the only possibility of selecting for age is by varying the second term (we discuss this assumption in the main text). The second factors are the probabilities that a fish of age group $j = I, M$ is actually retained in the net, contingent on the fact that the fish has already entered it. These probabilities are described by logistic functions, that are characterized by the parameters α_j and β_j. They differ for the two age groups, because the larger, mature cod have a higher probability of being retained in the net than the smaller, immature cod. To be able to derive a closed-form cost function, we assume $\alpha_M = 2\,\alpha_I$ and consider mesh-sizes $m_t > (2\,\beta_I - \beta_M)$. For the Eastern Baltic cod fishery, these conditions hold for mesh-sizes larger than 3 cm, which is small compared to mesh sizes that would comply with current regulation (see Appendix A.5 and Table A.5). We now turn to deriving the cost function (12). Note that both E_t and m_t can be considered as input variables into the fishery. The cost function is obtained by minimizing harvesting costs over E_t and m_t for given (feasible) harvest levels H_{jt} and stock size X_{jt}, $j = I, M$. Assuming a price ζ for effort and costless choice of mesh size, we obtain the following cost function from (21b)

$$C(H_{It}, H_{Mt}, X_{It}, X_{Mt}) = \min_{m_t} \left\{ \frac{\zeta}{1-\epsilon} \, \frac{X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}}{\eta_M\,(m_t)} \right\}. \tag{23}$$

Dividing (21b) by (21a), and using (22) yields

$$\frac{X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}}{X_{It}^{1-\epsilon} - (X_{It} - H_{It})^{1-\epsilon}} = \frac{\eta_M(m_t)}{\eta_I(m_t)} = \frac{1 + \exp\left(\frac{m_t - \beta_I}{\alpha_I}\right)}{1 + \exp\left(\frac{m_t - \beta_M}{\alpha_M}\right)} \tag{24}$$

Under the above assumptions $\alpha_M = 2\,\alpha_I$ and $m_T > 2\,\beta_I - \beta_M$, this equation has a unique solution $m^\star(H_{It}, H_{Mt}, X_{It}, X_{Mt})$, which then also minimizes the right-hand side of (23). As $\alpha_M = 2\,\alpha_I$, we have $\exp\left(\frac{m_t - \beta_I}{\alpha_I}\right) = \left(\exp\left(\frac{m_t - \beta_I}{\alpha_M}\right)\right)^2$ and $\exp\left(\frac{m_t - \beta_M}{\alpha_M}\right) = \omega^{\frac{1}{2}} \exp\left(\frac{m_t - \beta_I}{\alpha_I}\right)$, where $\omega = \exp\left(-\frac{\beta_M - \beta_I}{\alpha_I}\right)$. Equation (24) reduces to a quadratic equation that can be transformed to (writing for short $m^\star = m^\star(H_{It}, H_{Mt}, X_{It}, X_{Mt})$)

$$\frac{\eta_0}{\eta_M(m^\star)} = 1 + \exp\left(\frac{m^\star - \beta_M}{\alpha_M}\right) = 1 + \frac{\omega}{2} \frac{X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}}{X_{It}^{1-\epsilon} - (X_{It} - H_{It})^{1-\epsilon}} \cdot$$
$$\left(1 + \sqrt{1 + \frac{4}{\omega} \frac{X_{It}^{1-\epsilon} - (X_{It} - H_{It})^{1-\epsilon}}{X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}} \left(1 - \frac{X_{It}^{1-\epsilon} - (X_{It} - H_{It})^{1-\epsilon}}{X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}}\right)}\right) . \quad (25)$$

Using this result in (23) and defining the cost parameter $c = \zeta/\eta_0$ leads to (12). In the following appendices, we derive the parameter values (ϵ, η_0, α_I, β_I, α_M, β_M, and ζ) for applying this cost function to the Eastern Baltic cod fishery.

A.5. Estimation of gear selectivity parameter for cost function (12)

In this section, we derive the gear parameters α_j and β_j, $j = I, M$, determining gear selectivity. For this, we use information on (i) the "gear selection curve" and (ii) the length distribution of age group $j = I, M$ (the age-length key).

(i) The gear selection curve gives the fraction of fish retained in the net as a function of the mesh-size m_t and the length l of the fish. For a trawl net, it is well described by a logistic function (cf. Madsen 2007; Wileman et al. 1996)

$$\left(1 + \exp\left(\ln(9)\, \frac{l_{50}(m_t) - l}{l_{75}(m_t) - l_{25}(m_t)}\right)\right)^{-1}, \quad (26)$$

where $l_x(m_t)$ is the length at which $x\%$ of the fish are retained when mesh size is m_t. For a typical net used to catch Baltic cod (one with the Bacoma escape window), these parameters depend on the mesh-size as follows (cf. Madsen 2007):

$$l_{50}(m_t) = 3.79\, m_t \quad (27a)$$
$$l_{75}(m_t) - l_{25}(m_t) = 0.557\, m_t, \quad (27b)$$

where both the length of the fish (l) and mesh-size (m) are measured in centimeters.

(ii) For the age-length keys, we assume that the lengths of both immature and mature cod are normally distributed. We estimate the mean and the standard deviation of both length distributions using data obtained from the Baltic International Trawl Survey (i.e. size and age measurements). This survey is designed to cover the complete distributional area of central Baltic cod (ICES, 2010) using a standardized trawl. For immature cod we use the average length-at-age data of two-year old cod in the second quarter of the years 1985 to 1994. For mature cod we use the mean of these length-at-age distributions for cod of three years and older weighted at the relative abundances of these year classes in the mean of 1985 to 1994 (numbers at age taken from ICES (2010)). The resulting mean and standard deviation of the age-length keys are $\mu_I = 28.0$ and $\sigma_I = 6.1$ for immature cod and $\mu_M = 44.6$ and $\sigma_M = 12.1$ for mature cod (all in cm).

The probabilities $\eta_I(m_t)/\eta_0$ and $\eta_M(m_t)/\eta_0$ for both age groups of being retained in a net with mesh-size m are calculated as convolutions of the selection curve and the age-length keys,

$$\frac{\eta_I(m_t)}{\eta_0} = \int_0^\infty \frac{1}{\sqrt{2\,\pi}\,\sigma_I} \frac{\exp\left(-\frac{(l-\mu_I)^2}{2\,\sigma_I^2}\right)}{1+\exp\left(\ln(9)\,\frac{l_{50}(m_t)-l}{l_{75}(m_t)-l_{25}(m_t)}\right)}\,dl \tag{28a}$$

$$\frac{\eta_M(m_t)}{\eta_0} = \int_0^\infty \frac{1}{\sqrt{2\,\pi}\,\sigma_M} \frac{\exp\left(-\frac{(l-\mu_M)^2}{2\,\sigma_M^2}\right)}{1+\exp\left(\ln(9)\,\frac{l_{50}(m_t)-l}{l_{75}(m_t)-l_{25}(m_t)}\right)}\,dl \tag{28b}$$

These expressions cannot be calculated analytically. In particular, they are not exactly logistic functions of m_t, as assumed in Equations (22a) and (22b) in Appendix A.4. They can however be well approximated by logistic functions.

We determine the selectivity parameters by means of a nonlinear OLS regression of the logistic functions in (22a) and (22b) to values of $\epsilon_I(m_t)$ and $\epsilon_M(m_t)$ computed from (28a) and (28b). This leads to the estimates $\alpha_I = 1.09$, $\beta_I = 7.44$, $\alpha_M = 2.08$, and $\beta_M = 11.86$ (all in cm).

Thus the assumption $\alpha_M = 2\,\alpha_I$ made for deriving the cost function (12) holds with good approximation. Furthermore, For the parameter ω of cost function (12), we obtain the value $\omega = \exp\left(-\frac{\beta_M-\beta_I}{\alpha_I}\right) = 0.017$.

A.6. Estimation of catchability and stock elasticity for cost function (12)

To estimate the parameters η_0 and ϵ, we use effort data measured in days at sea for the Danish fleet for the years 1987–2007 from ICES (2008). Dividing the effort of the Danish fleet by its harvesting share (also from ICES 2008), we obtain an estimate for total effort. To account for the selectivity of the trawl nets used, we assume that trawlers use standard trawl nets (years 1987–2003) or nets with Bacoma escape windows (years

2004–2007) with the respective minimum legal mesh-sizes $m_{\min}$ according to current European regulations. The regulations and the estimates of the expression $\epsilon_M(m_{\min})$ are reported in Table 2.

year	minimum landing size [cm]	trawl net type	minimum mesh-size $m_{\min}$ [cm]	$\epsilon_M(m_{\min})$
1987	30	Standard (sPA)	9.0	0.8743
1988	30	Standard (sPA)	9.5	0.8448
1989	32	Standard (sPA)	10.0	0.8115
1990	33	Standard (dPE)	10.5	0.8770
1995	35	Standard (dPE)	12.0	0.7375
2002	35	Standard (dPE)	13.0	0.6188
2003	38	Standard (dPE)	14.0	0.4930
2004	38	Bacoma window	11.0	0.5890

Table 2: European regulation from the respective year onwards. For some years other trawl net types were also allowed (Madsen, 2007, Table 4). “sPA” means single polyamide netting, “dPE” means double polyethylene netting, Bacoma is an escape window in the trawl net’s codend consisting of square meshes with knotless polyethylene netting. The estimated fraction of mature cod retained in trawl nets $\epsilon_M(m_{\min})$ is calculated using the selection-curve estimates from Madsen (2007) and the age-length key as derived in Appendix A.5.

For stock numbers and harvests, we use data from ICES (2008) stock assessment. We use this data to estimate the equation

$$E_t = \frac{1}{\eta_0\, \epsilon_M(m_{\min})\, (1-\epsilon)} \left(X_{Mt}^{1-\epsilon} - (X_{Mt} - H_{Mt})^{1-\epsilon}\right) \tag{29}$$

Under a non-linear OLS regression of the harvesting function allowing for $\epsilon < 1$, we obtain an estimate $\epsilon = 1.11$. We could not reject the null hypothesis $\epsilon = 1$ (the p-value for $\epsilon = 1$ is 0.66). Using $\epsilon = 1$ in (29) and applying an OLS regression to the resulting equation $\ln\left(X_{Mt}/\left(X_{Mt} - H_{Mt}\right)\right) = \eta_0\, \epsilon_M(m_{\min})\, E_t$ gives an estimate $\eta_0 = 8.26 \cdot 10^{-6}$ per day at sea with a standard error of $0.98 \cdot 10^{-6}$.

A.7. Estimation of effort cost parameter for cost function (12)

The variable costs of fishing per day at sea are calculated according to Kronbak (2002, 2005), using data from Fiskeriregnskabsstatistik (2007) for fishing vessels operating in the region of Bornholm, a major fishing area in the Eastern Baltic Sea, for the years 1996 to 2007. To obtain the variable costs per day at sea in Danish crowns (DKK), the variable cost of harvesting cod is divided by the days at sea on which a firm is harvesting cod in the Bornholm region. The variable cost of harvesting cod is obtained as the product of variable cost (in 1000 DKK per firm) and the share of cod (gross output in the cod fishery divided by gross output in total). The variable costs are derived by adding the labor cost of fishermen and total cost (in 1000 DKK per firm) and subtracting depreciation. We convert the cost parameter measured in DKK into real terms by dividing it by the output price of cod to avoid issues of inflation and currency conversion. The resulting average unit effort cost parameter (in real terms) $\tilde{\zeta} = 554$ [kg/day at sea] is obtained as the average for 1995 to 2007, using the estimations of Kronbak (2002) for the years 1995–1999, and own calculations for the years 2000–2007. The standard error of cost/price ratios is 84.7 [kg/day at sea].

For the cost parameter we thus obtain $c = p_M\,\tilde{\zeta}/\eta_0 = 1.095 \cdot 554/(8.26 \cdot 10^{-6})$ euros $= 72.9$ million euros. The standard error is $72.9 \cdot (84.7/554 + 0.98/8.26)$ million euros $= 19.8$ million euros.

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