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Conference Paper

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Beiträge zur Jahrestagung des Vereins für Socialpolitik 2010: Ökonomie der Familie - Session:
Optimal Resource Extraction, No. A15-V3

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Quaas, Martin; Requate, Till; Ruckes, Kirsten; Skonhoft, Anders; Vestergaard, Niels (2010) : Incentives for Optimal Management of Age-structured Fish Populations, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2010: Ökonomie der Familie - Session: Optimal Resource Extraction, No. A15-V3, Verein für Socialpolitik, Frankfurt a. M.

This Version is available at:

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Incentives for Optimal Management of Age-structured Fish Populations

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February 25, 2010

Abstract: We study optimal fishery management in an age-structured, bio-economic model where two age classes can be harvested independently. We show that the optimal amount of catch differs with age classes, and we derive conditions under which it is optimal to harvest only one age class. Our main policy implication is that optimal age-structured harvesting can be implemented by a single total allowable catch (TAC) and tradable harvesting quotas, where the latter are specified in terms of the *number* of fish harvested rather than in terms of biomass. In this case, gear restrictions (such as mesh-size prescriptions) turn out to be obsolete. We then apply our model to Eastern Baltic cod fishery.

JEL-Classification: Q22, Q57

Keywords: fishery management, optimal harvesting, harvesting fees, bioeconomics, age-structured model

1. Introduction

In all economic problems where market failure arises economists typically ask two questions: first, what do efficient allocations look like, and secondly, how can these allocations be implemented through decentralized decision-making. This procedure also applies to problems in the optimal management of fish stocks. The workhorse model for answering these questions is the biomass (or lumped-parameter) model, which describes the dynamics of a fish stock in terms of its biomass (Gordon 1954, Scott 1955, Clark 1990). This model has often been criticized for oversimplifying biological structures and thus for generating inadequate management recommendations.¹ The crucial weakness of the surplus-production model is that it is incapable of distinguishing between two aspects of overfishing: recruitment overfishing and growth overfishing. Recruitment overfishing refers to the problem of low reproduction, because the spawning stock is has been fished down. Growth overfishing, by contrast, means that fish are caught at an inefficiently low age and weight class. In order to distinguish between these two 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 incentive-based policy instruments. We first study optimal harvesting by asking which age classes should be harvested at all and what are the optimal amounts of catch for each age class. For this purpose we set up a simple dynamic cohort model with four age classes: eggs and larvae, juveniles, young fish at edible size but non-spawning age, and mature fish at spawning age. Only the young and mature fish are subject to potential harvest. We

¹ Tahvonen (2009a;b) provides an overview of the criticism leveled at applying the biomass model in the economics of fisheries.

consider selective fishing technology, which means that fishermen target the young and mature age groups independently. We use the concept of fishing technology in a broad sense in that fishermen may choose different types fishing gear and the time and location of harvest. Thus, fishermen's selective harvesting options are richer than the regulator's options for imposing selective harvesting by means of command-and-control.

Based on the results on optimal harvesting we ask how optimal management can be implemented by means of incentive-based economic instruments such as fees or tradable quotas. We show that fixing the total allowable catch (TAC) and issuing tradable quotas², measured in terms of *biomass*, an instrument that is currently used in many fisheries³ is bound to fail as a solution for the problem of growth overfishing. This 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 more easily. We show that a single TAC and tradable quotas measured in terms of the *number* of fish rather than in terms of biomass implements the first-best harvesting rule if natural survival rates of the different age classes subject to harvesting are identical. If natural survival rates differ with age, the instrument has to be modified slightly: the quotas for different age classes have to be traded at a fixed “exchange rate” that depends on the ratio of survival rates, and the TAC has to be adjusted accordingly. Furthermore we show how a

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, and several member states of the European Union.

related price-based instrument in terms of harvesting fees can also implement the first-best harvesting rule. With the economic instruments we propose, additional regulations in terms of gear restrictions (such as mesh-size prescriptions) or minimum landing-sizes are obsolete. Finally, to quantify both the total allowable catch and the quota price for a real fish population, we apply our model and analysis to the case of the Eastern Baltic cod fishery.

The number of previous 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;c) has significantly advanced the analysis of optimal harvesting age-structured fish stocks. He in particular studies the effects of different types of gear selectivity. One type is “knife-edge” selectivity (Beverton and Holt 1957). This means that all age classes above a certain age are subject to fishing mortality, while all younger and smaller fish completely escape. The other type is non-selective fishing gear, which implies that all age classes are harvested in fixed (but not necessarily equal) proportions. With non-selective gear, the optimal harvesting strategy may be “pulse-fishing”, where all fish are harvested at certain points in time with no fishing in between. The present paper differs from the previous studies by considering a perfectly selective fishing technology (in the broad sense discussed above) and by also suggesting new incentive-based policy instruments to decentralize optimal harvesting rules of age structured fish populations .

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

2. Analytical Bio-Economic Model of an Age-structured Population

2.1 Population model

In this section we set up a simple model of an age-structured fishery that is sufficiently rich to analyze harvesting of different age classes. The fish population at time (year) t is divided into four stages: eggs and larvae $X_{E,t}$ (age < 1), juveniles $X_{J,t}$ ($1 \leq \text{age} < 2$), young immature fish $X_{I,t}$ ($2 \leq \text{age} < 3$), and mature fish $X_{M,t}$ (age ≥ 3). All stocks, $X_{j,t}, j \in \{E, J, I, M\}$ are measured in numbers of fish. Both eggs and larvae (age class E) and juveniles (age class J) are assumed to be sufficiently small for them not to be subject to fishing mortality. In principle these two age classes could be lumped together in one class; we keep them separate to avoid time lags of different lengths. Age class I consists of immature, non-spawning fish that are sufficiently large to be of commercial value. Age class M consists of all mature fish that are three years and older. This age class is the spawning stock.

In a single time period (a year) four events occur in the following order: In the first step mature fish spawn, and in the second step fishermen harvest. In the third step, natural mortality further reduces the stocks of all classes, and finally somatic growth of individual fish takes place.⁴

To describe the population dynamics, we start with recruitment. The stock of age-class 0 (eggs and larvae) in year $t+1$ depends on the size of the spawning stock and is governed by a non-linear recruitment function $r(X_{M,t})$ of the spawning stock in period t , with $r(0)=0$ and

⁴ Generally, all these events may occur simultaneously during parts of the time period (Beverton and Holt 1957). However, the assumption of a particular order substantially simplifies the analysis. None of our central findings depend on this assumption.

$r'(X_{M,t}) > 0$ for at least some range of $X_{M,t}$. An example of such a non-linear recruitment function is the Ricker function that we use in the case study (Section 4).

Only age classes 2 and 3 are subject to fishing mortality, while all age classes are subject to natural mortality, which is assumed to be fixed and independent of the density of the fish population. The coefficients $b_{i,j} > 0$ are the survival rates from age class i to age class j . Denoting harvest quantities of age classes I and M by $H_{I,t}$ and $H_{M,t}$, we obtain the escapement stocks $S_{I,t}$ and $S_{M,t}$, i.e. the numbers of fish that escape from harvesting, according to the rule

$$S_{j,t} = X_{j,t} - H_{j,t} \quad j = I, M \quad (1)$$

The equations of motion describing the dynamics of the age-structured fish stock subject to harvesting are⁵

$$\begin{aligned} X_{E,t+1} &= r(X_{M,t}) \\ X_{J,t+1} &= b_{EJ} X_{E,t} \\ X_{I,t+1} &= b_{JI} X_{J,t} \\ X_{M,t+1} &= b_{IM} S_{I,t} + b_{MM} S_{M,t} \end{aligned} \quad (2)$$

The equilibrium properties of models with a similar structure (density-dependent recruitment and density-independent natural mortality) and the conditions for maximum sustainable yields have been analyzed by Reed (1980). Here we focus on economically optimal harvesting and dynamics, and we investigate how first-best harvesting rules can be implemented by economic management instruments. For this purpose, we now turn to the economic part of the bio-economic model.

⁵Alternatively, the population dynamics can be described by a Leslie Matrix with non-constant entries (e.g. Getz and Haight 1989).

2.2 Harvesting and profit

As mentioned above, we assume that fishermen can perfectly select the age class they are targeting. A high degree of selectivity may be possible for several reasons. For some species, selection of age classes is possible by choosing fishing grounds, as different cohorts can be found in different regions. Also, some passive gear types, such as traps, allow the targeting of specific size classes with a comparatively high degree of precision.

Annual profits are determined by the revenues from harvesting both age classes, given by $p_I w_I [X_{I,t} - S_{I,t}] + p_M w_M [X_{M,t} - S_{M,t}]$, and by the harvesting cost of either age class. In Appendix A we show that, with an instantaneous harvesting function of a generalized Gordon-Schaefer type, annual harvesting cost of age class j is given by $\frac{c_j}{1-\beta} [X_{j,t}^{1-\beta} - S_{j,t}^{1-\beta}]$.

In order to determine optimal harvesting of the age-structured fish stock, we consider a central planner who determines the escapements of both age classes optimally. The planner's objective is to maximize the present value of annual profits discounted at a constant factor $\rho \in (0,1)$ ⁶. The intertemporal objective function is thus given by

$$V = \sum_{t=0}^{\infty} \rho^t \left[p_I w_I [X_{I,t} - S_{I,t}] + p_M w_M [X_{M,t} - S_{M,t}] - \frac{c_I}{1-\beta} [X_{I,t}^{1-\beta} - S_{I,t}^{1-\beta}] - \frac{c_M}{1-\beta} [X_{M,t}^{1-\beta} - S_{M,t}^{1-\beta}] \right] \quad (3)$$

Here p_j is the price per kilogram and w_j is the weight of an individual fish of age $j = I, M$. The parameter $\beta \in (0,1]$ is the stock elasticity of harvest (sometimes also called the “schooling

⁶ It can be shown that our general results on fishery management also hold for an objective function that is nonlinear in profits.

parameter’’).⁷ In Appendix A we show that the cost parameters $c_j = \nu_j / \eta_j$ are increasing with the unit effort costs ν_j and decreasing with the catchability coefficients η_j .

The central planner maximizes (3) subject to the population dynamics (2), together with the given initial number of fish in all four age classes $X_{i,0}$ ($i = E, J, I, M$) and the constraints that escapement must be positive (to exclude depletion of the stock) but no larger than the current stock $0 < S_{j,t} \leq X_{j,t}$, $j = I, M$.

2.3 Conditions for optimal economic management

The necessary conditions for the optimal harvesting of the age-structured fish stock are obtained by applying the Lagrangian method together with the appropriate Kuhn-Tucker conditions. With $\lambda_{i,t} > 0$ ($i = A, J, I, M$ and $t = 0, \dots, \infty$) as the Kuhn-Tucker multipliers of the population growth equations (2) and $\mu_{j,t} \geq 0$, $j = I, M$ and $t = 0, \dots, \infty$ as the Kuhn-Tucker multipliers of the escapement constraints, $0 < S_{j,t} \leq X_{j,t}$ the Lagrangian function is given by

$$\begin{aligned} L = \sum_{t=0}^{\infty} \rho^t \{ & p_I w_I [X_{I,t} - S_{I,t}] + p_M w_M [X_{M,t} - S_{M,t}] - \frac{c_I}{1-\beta} [X_{I,t}^{1-\beta} - S_{I,t}^{1-\beta}] - \frac{c_M}{1-\beta} [X_{M,t}^{1-\beta} - S_{M,t}^{1-\beta}] \\ & + \lambda_{E,t} [r(X_{M,t}) - X_{E,t+1}] + \lambda_{J,t} [b_{EJ} X_{E,t} - X_{H,t+1}] + \lambda_{I,t} [b_{JI} X_{J,t} - X_{I,t+1}] \\ & + \lambda_{M,t} [b_{IM} S_{I,t} + b_{MM} S_{M,t} - X_{M,t+1}] \\ & + \mu_{I,t} [X_{I,t} - S_{I,t}] + \mu_{M,t} [X_{M,t} - S_{M,t}] \} \end{aligned} \quad (4)$$

The first-order necessary conditions for optimal harvesting are

⁷ The lower limit $\beta = 0$ describes a fish stock with strong schooling behavior, while the upper limit $\beta = 1$ describes a highly dispersed fish stock (Hannesson 1983).

$$\begin{aligned} \rho^{-t} \frac{\partial L}{\partial S_{I,t}} &= 0 & p_I w_I - c_I S_{I,t}^{-\beta} + \mu_{I,t} &= \lambda_M b_{IM} \\ & & \mu_{I,t} [X_{I,t} - S_{I,t}] &= 0 \end{aligned} \tag{5}$$

$$\begin{aligned} \rho^{-t} \frac{\partial L}{\partial S_{M,t}} &= 0 & p_M w_M - c_M S_{M,t}^{-\beta} + \mu_{M,t} &= \lambda_{M,t} b_{MM} \\ & & \mu_{M,t} [X_{M,t} - S_{M,t}] &= 0 \end{aligned} \tag{6}$$

$$\rho^{-t} \frac{\partial L}{\partial X_{E,t}} = 0 \quad \rho b_{EJ} \lambda_{J,t} = \lambda_{E,t-1} \tag{7}$$

$$\rho^{-t} \frac{\partial L}{\partial X_{J,t}} = 0 \quad \rho b_{JI} \lambda_{I,t} = \lambda_{J,t-1} \tag{8}$$

$$\rho^{-t} \frac{\partial L}{\partial X_{I,t}} = 0 \quad \rho [p_I w_I - c_I X_{I,t}^{-\beta} + \mu_{I,t}] = \lambda_{I,t-1} \tag{9}$$

$$\rho^{-t} \frac{\partial L}{\partial X_{M,t}} = 0 \quad \rho [p_M w_M - c_M X_{M,t}^{-\beta} + \mu_{M,t} + \lambda_{E,t} r'(X_{M,t})] = \lambda_{M,t-1} \tag{10}$$

Analysis of these conditions leads to a number of clear-cut results about optimal harvesting and management of the age-structured fish stock, to be discussed in the following two sections. A first set of results (presented in Section 3) characterizes optimal harvesting of the age-structured fish population under different conditions on biological parameters, costs and prices. The second set of results (presented in Section 4) show how optimal management of the age-structured fish population can be decentralized by using suitable economic instruments.

3. Optimal harvesting structure

In our first result on optimal harvesting we show that under reasonable assumptions on market prices, harvest costs, and survival rates, optimal escapement of immature (age class I) is

larger than optimal escapement of mature fish (age class M). For both age classes, optimal escapement is governed by the trade-off between current benefit of immediate harvesting and future benefits in terms of next periods' harvest and increased recruitment. The trade-off is different for the two age classes mainly because current benefits differ. Mature fish are usually much larger than young fish, and often have a higher market price per kilogram. Thus, revenues are greater for mature than for immature fish. If harvesting cost functions are similar for both age classes, this implies that the current benefit of immediate harvesting is higher for mature than for immature fish. Future benefits are the same for both age classes, as immature fish become mature and thus contribute to the next period's spawning stock, just as the surviving mature fish. The weight of future benefits in the trade-off may be different for both age classes as natural survival rates may differ with age. Since volatility of survival rates is typically low, it is reasonable to conclude that there is a higher benefit from escapement of immature fish than of mature fish.

Formally, we can state our first result as follows.

Proposition 1. *If $p_M w_M / b_{MM} > p_I w_I / b_{IM}$ and $c_M / b_{MM} \leq c_I / b_{IM}$, optimal escapement of immature fish is larger than optimal escapement of mature fish if the stock of immature fish is large enough to allow harvesting, $S_{I,t} < X_{I,t}$.*

Proof: If we divide condition (5) by b_{IM} and condition (6) by b_{MM} , the right-hand sides of both conditions are identical. If $p_M w_M / b_{MM} > p_I w_I / b_{IM}$, the first term on the left-hand side (LHS) of (5) is smaller than the first term on the LHS of (6). For $\mu_{I,t} = 0$, and with $\mu_{M,t} \geq 0$, we conclude from (5) and (6) that $c_I / b_{IM} S_{I,t}^{-\beta} < c_M / b_{MM} S_{M,t}^{-\beta}$. Hence $S_{I,t} > S_{M,t}$, given that $c_M / b_{MM} \leq c_I / b_{IM}$.

The condition $p_M w_M / b_{MM} > p_I w_I / b_{IM}$ has a straightforward economic interpretation: $p_j w_j / (b_{jM} \lambda_{M,t})$, $j = I, M$, is the ratio of benefit from immediate harvest to opportunity cost in terms of future harvests at time t . The condition states that this ratio is always larger for the older age class than for the younger one. The condition $c_M / b_{MM} \leq c_I / b_{IM}$ implies a corresponding relationship for the harvesting costs. As discussed above, the conditions of the proposition are likely to hold for many fisheries.

Since all fish of three years and older are grouped in the stock of mature fish, the number of mature fish may well be larger than the number of immature fish in the same year. If this is the case, Proposition 1 implies that the optimal number of immature fish harvested must be smaller than that of mature fish.

Our next result on optimal harvesting states that optimal harvest (and therefore the optimal TAC) of immature fish is always zero if harvesting cost are independent of stock sizes, i.e. if $\beta = 0$, and if the conditions on prices, cost parameter, and survival rates apply as discussed before. This is because for stock-independent harvesting cost, the trade-off between current and future benefits is independent of the level of escapement. It is then always better to let all of the immature fish grow, become mature and spawn, and to harvest mature fish only. This is formally stated in the following proposition.

Proposition 2. *If harvesting costs are independent of stock sizes, i.e. $\beta = 0$, and if $p_M w_M / b_{MM} > p_I w_I / b_{IM}$ and $c_M / b_{MM} \leq c_I / b_{IM}$, then the optimal harvest of immature fish is zero; that is, $S_{I,t} \equiv X_{I,t}$ for all t .*

Proof: For $\beta = 0$, the result $\mu_{I,t} > 0$ and zero harvest of immature fish follow from conditions (5)

and (6) under the assumptions $p_M w_M / b_{MM} > p_I w_I / b_{IM}$ and $c_M / b_{MM} \leq c_I / b_{IM}$, together with non-negative Kuhn-Tucker multipliers of the escapement constraints.

For schooling fish such as the North Sea herring, Bjorndal (1988) finds the harvesting cost to be approximately independent of stock size (see also Hannesson 1983). For such fisheries, complete escapement, i.e. zero harvest, of immature fish is optimal under the conditions discussed above. For many fisheries, however, it is more plausible that harvesting costs decrease with stock sizes. Therefore, our next result on optimal harvesting provides a condition, under which zero harvest of immature fish is optimal when harvesting cost decrease with the stock size. For analytical reasons, we concentrate on a steady state. A sufficient condition for zero harvest of immature fish is that the revenue of harvesting one immature fish in the current period is smaller than the *present value* of harvesting one mature fish one period later, and that harvesting costs of mature fish do not exceed those of immature fish at an equal stock size, i.e. if $c_M \leq c_I$. Note that in a steady state all stocks and all current-value shadow prices are constant, i.e. $X_{j,t+1} = X_{j,t} = X_j$,

$S_{j,t+1} = S_{j,t} = S_j$, and $\lambda_{j,t-1} = \lambda_{j,t} = \lambda_j$ for $j = E, J, I, M$. Using these conditions in the population dynamics (2) and the optimal control conditions (5-10), we obtain the following sufficient (but not necessary) condition for complete escapement of young immature fish in the optimal steady state.

Proposition 3. *If $c_M \leq c_I$ and*

$$b_{IM} \rho p_M w_M > p_I w_I \quad (11)$$

hold, then the optimal harvest of immature fish is zero in the steady state; that is, $S_I = X_I$ in the

steady state.

Proof: See Appendix B.

As discussed above, the value of a mature fish harvested is usually larger than the value of an immature fish, that is, $p_I w_I < p_M w_M$. Inequality (11), however, provides a condition on the present values of mature and immature fish, which is obtained by discounting the value of mature fish by both the money-value discount factor ρ and the rate of survival b_{IM} from age class I to M which may be interpreted as a biological discount factor. If the money-value discount factor is not too high, Condition (11) is met for many fisheries. For the case of Eastern Baltic cod, for example, this holds for discount factors $\rho > 0.57$ (or discount *rates* lower than 76%, see Section 5).

One general conclusion from these results is that optimal harvest quantities of immature and mature fish differ. Thus to implement the optimal harvesting policy through quota setting (TAC), different TACs would have to be used for the two age classes. A second general conclusion is that corner solutions with a zero TAC for immature fish may well be optimal, depending on biological parameters (survival rates and body-weight growth rates), but also on prices and cost parameters. In theory, a zero TAC for immature fish could be implemented by a gear regulation that excludes the harvesting of two-year-old fish. Practically, however, such a policy is not easy to implement, because it would require the regulator to prescribe a certain knife-edge selectivity of fishing gear. However, most specific types of fishing gear select only imperfectly for age.

4. Decentralization through incentive-based policy instruments

In this section we study how optimal harvesting structures as characterized above can be decentralized by implementing incentive-based policy instruments such as harvesting fees and tradable harvesting quotas.⁸ Starting with harvesting fees, it is intuitive to guess that two harvesting fees are necessary to achieve the first best harvesting structure: one on the number of immature another one on the number of mature fish harvested. These fees capture the marginal opportunity costs of harvesting in terms of foregone future benefits of the stock of mature fish, i.e. next periods' harvest and increased recruitment. In general, two different harvesting fees are needed, as the age-specific survival rates may differ, and thus the rates at which escapement of immature and mature fish contribute to the next period's spawning stock. Harvesting fees exhibit two features rendering them the more attractive instrument compared with a set of different age-specific TACs. First, since the fees differ only by the constant survival rates b_{IM} and b_{MM} , the ratio of the fees is always constant even on the transitional path into a steady state. Second, no explicit distinction between an "interior" solution with positive harvesting quantities and a "corner" solution with zero harvest (complete escapement) of immature fish is necessary. The reason is that in the latter case the optimal harvesting fee for immature fish exceeds the marginal

⁸In the literature on fisheries, price-based instruments are frequently 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. Since harvested fish may be discarded rather than landed, a landing fee may not be the appropriate instrument for implementing optimal management.

profit of harvesting the first fish. In the formal proposition we use $\varphi_{j,t}$ to denote the harvesting fee for age class j in year t .

Proposition 4. *Optimal harvest of both age classes can be decentralized by setting two harvesting fees on the number of immature and mature fish, given by $\varphi_{I,t} = b_{IM} \lambda_{M,t}$ and $\varphi_{M,t} = b_{MM} \lambda_{M,t}$*

Proof: For $\mu_{I,t} = \mu_{M,t} = 0$ and harvest in both stages, this follows immediately from conditions (5) and (6). For $\mu_{j,t} > 0$, $j = I, M$, we have $p_j w_j - c_j X_{j,t}^{-\beta} > \varphi_j$. Hence, $S_{j,t} = X_{j,t}$ is optimal for individual fishermen, as is the social optimal solution.

Decentralizing the optimal harvest structure by fees is even simpler if the survival rates of immature and mature fish are identical. In this case a single fee for all age classes is sufficient to decentralize the social optimum. The assumption of equal survival rates for the different age classes is appropriate for several fisheries, including the Eastern Baltic cod fishery studied in Section 4. Formally, this result is a corollary to Proposition 4.

Corollary 1. *If $b_{IM} = b_{MM}$, a single fee $\varphi_t = b_{IM} \lambda_{M,t} = b_{MM} \lambda_{M,t}$ on the number of harvested fish decentralizes the optimal harvest of both age classes.*

It is important to note that the harvesting fee is related to the *number* of fish harvested, not to the *weight* of catch. Let us consider the case of identical survival rates to illustrate the important difference between the instrument proposed here and a traditional harvesting fee on weight resulting from the biomass model. In particular, we want to demonstrate that an unmodified “biomass” fee may generate inadequate incentives to fishermen. To see this we use $\tilde{\varphi}_t^{b-m}$ to denote a fee per kilogram harvested. Converting this into a fee per fish of age class j we

obtain $w_j \tilde{\varphi}_t^{b-m}$, as a fish of age-class j has a weight of w_j kilograms. Thus, the fee per individual immature fish derived from a uniform “biomass” fee is much smaller than corresponding fee per individual mature fish, i.e. $w_M \tilde{\varphi}_t^{b-m} \gg w_I \tilde{\varphi}_t^{b-m}$, as normally $w_M \gg w_I$. This implies that a uniform biomass fee induces a considerable distortion towards over-harvesting of immature fish. Put differently, the optimal fee per kilogram of immature fish would have to be higher than the optimal fee per kilogram of mature fish. It is easy to see that also for the case of different survival rates, a “biomass” harvesting fee will also induce a distortion towards over-harvesting of immature fish.

Next we study tradable harvesting quotas as the corresponding quantity-based economic instrument. Similar to management by fees, the important difference to traditional management systems is that both the total allowable catch and the quotas are measured in numbers of fish rather than in units of biomass. If the survival rates of immature and mature fish are identical, optimal harvesting can be implemented by means of a single TAC and a system of individual tradable harvesting quotas that can be traded on a one-to-one basis. Note that the regulator does not need to prescribe the allocation of quotas among the different age classes, as this is done by the quota market. This result is formally stated in the following proposition.

Proposition 5. *If $b_{IM} = b_{MM}$, the optimal harvest of both age classes is decentralized by setting a total allowable catch of size $X_{I,t} - S_{I,t} + X_{M,t} - S_{M,t}$ on the overall number of fish harvested and implementing it by means of tradable harvesting quotas in numbers.*

Proof: see Appendix C.

If, by contrast, the survival rates of immature and mature fish differ, the instrument has to

be modified slightly. Harvesting quotas must then not be traded on a one-to-one basis among age classes, but on the basis of a constant “exchange rate” determined by the ratio of survival rates, as the following corollary to Proposition 5 states.

Corollary 2. *If $b_{IM} \neq b_{MM}$, the optimal harvest of both age classes can be decentralized by setting*

- i) *a total allowable catch of size $b_{IM} / b_{MM} \cdot X_{I,t} - S_{I,t} + X_{M,t} - S_{M,t}$ on the overall number of fish harvested,*
- ii) *implementing the TAC by issuing tradable harvesting quotas in numbers and*
- iii) *fixing an exchange rate of b_{IM} / b_{MM} units of immature fish for one mature fish.*

In this setting, the harvesting quota may be thought of as a license to reduce the stock of fish of a particular age by no more than a specified amount.⁹ For harvesting a number h_I of immature fish (or a number h_M of mature fish), fishermen would need a license that allows them to reduce the spawning stock at the beginning of the next period by $b_{IM} h_I$ (or $b_{MM} h_M$) fish.

With a similar line of reasoning the traditional TAC/quota system in terms of biomass could be modified to decentralize optimal harvesting of the different age classes. A harvesting quota of one ton mature fish may be thought of as the license to reduce the current spawning stock by one ton, or, equivalently, as the license to reduce the spawning stock at the beginning of the next period by b_{MM} tons. In the same vein, a harvesting quota of one ton of immature fish may be thought of as the license to reduce the current stock of immature fish by one ton, or, equivalently, as the license to reduce the spawning stock at the beginning of the next period by $b_{IM} w_M / w_I$ tons. This is because b_{IM} currently immature fish that escape fishing would become

⁹ This interpretation of harvesting quotas is reminiscent of the Montgomery's (1972) concept of pollution licenses with exchange rates to account for the spatial dimension.

mature, accompanied by an increase in weight by a factor of w_M / w_I . In other words, the “biomass” quota system could be modified in such a way that one unit of the quota is needed to catch one ton of mature fish, while $(b_{IM} w_M / w_I) / b_{MM}$ units of the quota are needed to catch one ton of immature fish, where $(b_{IM} w_M / w_I) / b_{MM}$ will typically be much larger than one. For Eastern Baltic cod, for example, this exchange rate is 2.1 (see Section 5).

5. Application: Eastern Baltic Cod Fishery

The Eastern Baltic cod stock is historically the third largest stock in the North Atlantic (Dickson and Brander, 1993) with a long-term mean spawning stock biomass (SSB) of 400,000 to 500,000 tons. 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 the spawning stock biomass from over 600,000 to less than 100,000 tons, reaching a record low level in 2005 (66,000 tons; ICES 2009a). Landings by 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 ever since. Although the present estimates of stock biomass are uncertain due to misreporting of landings, discarding, and age-reading problems, the available information indicates that the SSB has recently increased. This is mainly due to the unusual strength of the 2005 and 2006 year classes (ICES, 2009b).

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, which

would correspond to an escapement of $\exp(-0.3) = 74\%$ of the stock. Besides setting the annual total allowable catch (TAC), the fishery is further managed through mesh size regulations (130 mm), minimum landing sizes (38 cm), seasonal fishery restrictions, and area closures mainly designed to protect spawning fish in the three main deep basins of the Baltic Sea, i.e., the Bornholm Basin, the Gotland Basin, and the Gdansk Deep (ICES, 2009b). The latter two management instruments are not the subject of this study and may well be part of an overall optimal fishery management. The two instruments that currently aim at preventing growth overfishing, mesh size regulations and minimum landing sizes, would be superfluous under a management by TAC and tradable harvesting quotas in terms of the *number* of fish, as proposed here. This would imply a significant reduction of transaction costs connected to monitoring and enforcement of these regulations.

5.1 Data and specific functional forms

The parameterization of the population model to the eastern Baltic cod case is based on best available biological data. Age-specific abundance data, the proportion of mature fish per age-class, and natural mortality rates are based on assessment data using a stochastic multispecies model (SMS; ICES 2008). The SMS is an advanced method applied in fish-stock assessment, which is routinely used in the Baltic. Compared to the more frequently used single-species virtual population analysis (VPA), it has the advantage of explicitly taking into account predation mortality as a density-dependent process. The weight of young immature fish ($w_I = 0.44$ kg/individual) is directly taken from the ICES (2009a) assessment report. The weight of mature fish ($w_M = 0.96$ kg/individual) was estimated as the mean weight of cod aged three

years and older, weighted at relative age-class-specific relative abundance from 1974-2007 (data from ICES 2009a).

We are not interested to calculate optimal stock numbers of eggs and juveniles. Accordingly, we estimate $r(X_M)$ as the stock-recruitment relationship 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 (2009a) assessment report. For short-term forecasting, ICES standard stock assessment does currently not use any stock-recruitment function but rather uses a geometric mean of years 1987-2005 (ICES 2009a). For our longer-term simulations, however, a stock-recruitment function is needed. We use the Ricker specification

$$r(X_M) = \gamma_1 X_M \exp -\gamma_2 X_M \quad (12)$$

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 of Baltic cod, as there are clear indications of increased cannibalism at high stock, mainly affecting juvenile fish. This phenomenon is due to a 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 used ICES (2008) data for the number of mature Eastern Baltic cod, $X_{M,t}$, and for the young immature recruits two years later, $R_{I,t+2}$, for the period 1974-2007. Taking logs of (12) and applying a simple OLS regression to $\ln(R_{I,t+2} / X_{M,t}) = \ln(\gamma_1) - \gamma_2 X_{M,t}$, we obtain $\gamma_1 = 1.54$ (standard error 0.159) and $\gamma_2 = 1.5 \cdot 10^{-9}/\text{fish}$ (standard error $0.61 \cdot 10^{-9}$). The peak value of

$X_M^{\text{peak}} = 1 / \gamma_2 = 667$ million individuals is about 10% greater than the spawning stock observed in the early 1980s (approx. 600 million individuals).

With weights below one kilogram, both immature and mature cod fall in the same size category. We therefore use $p_I = p_M$ in the simulation. According to European regulation (Council Regulation No 2406/96), 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 is increasing in 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 fall in this or an even higher size category, our assumption $p_I = p_M$ tends to overestimate the value of immature cod harvested. We normalize the price of mature cod to unity, i.e. $p_M = 1$, and calculate unit effort costs in terms of the average cost/price ratio.

For effort and cost, the data do not allow distinguishing between age classes. We therefore assume that harvesting functions and cost parameters are the same for immature and mature cod. To estimate the parameters of the harvesting function (see Appendix A), we use the stock numbers from the ICES (2008) report (years 1974-2007). We estimate escapement from stock numbers and the fishing mortalities reported in ICES (2008). Historical data on spawning stock numbers (SSN) and escapement from 1974 to 2007 are shown in Figure 1. Effort data, measured in days at sea, are available 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. Assuming stock elasticity of $\beta = 1$, an OLS regression of the harvesting function (see Appendix A) yields a catchability coefficient $\eta = 2.08 \cdot 10^{-6}$ (standard

error: $0.83 \cdot 10^{-6}$).¹⁰ Using the method of Kronbak (2005), and using data on Danish fishery accounts from 1995-2007, we obtain an average unit effort cost parameter of $\nu = 0.554$ (see Appendix D). With this, we obtain the cost parameter $c_M = c_I = \nu / \eta = 2.66 \cdot 10^5$.

Table 1 summarizes the parameters used in the following simulation. In the table we also report the 90% confidence intervals for the parameters estimated, i.e. γ_1 , γ_2 , η and ν , as well as an according interval of discount factors. We use these intervals for the sensitivity analysis of the numerical optimization.

Table 1 about here

5.2 Optimization results

From the parameters given in Table 1 we have $w_M / b_{MM} = 1.17$ and $w_I / b_{IM} = 0.54$. Hence the assumption $p_M w_M / b_{MM} > p_I w_I / b_{IM}$ is satisfied for Baltic cod. With $p_M \geq p_I$, condition (11) holds whenever $\rho > w_I / b_{IM} w_M = 0.57$, i.e. for annual discount rates lower than 76%. Assuming that this is the case, and as, by assumption, cost of harvesting immature cod is not lower than that of harvesting mature cod ($c_M \leq c_I$), it is optimal to exclusively harvest mature cod in a steady state (Proposition 3). In the optimal steady-state, the spawning stock consists of $X_M = 625$ million individuals, and the escapement of $S_M = 390$ million individuals (equations are given in Appendix B). The optimal steady-state spawning stock is slightly below the value representing the peak of the recruitment function (625 as compared to 667 million individuals).

¹⁰ We also performed a non-linear least-squares regression of the harvesting function allowing for $\beta < 1$. We could not reject the null hypothesis $\beta = 1$ at the 10% level. The assumption $\beta = 1$ is also supported by previous findings (Kronbak 2005, Hannesson 2007).

In order to assess the uncertainty involved in calculating the optimal steady state we perform the following sensitivity analysis: we calculate the optimal steady state for each combination of both the reference parameter set and the upper and lower boundaries of their confidence intervals (see Table 1). The resulting minimum and maximum steady-state values for the optimal steady state spawning stock are $\underline{X}_M = 327$ and $\bar{X}_M = 2824$ million individuals. For the optimal steady-state escapement, the corresponding minimum and maximum values are $\underline{S}_M = 322$ and $\bar{S}_M = 1941$ million individuals. These figures show that the optimal steady-state values are subject to considerable uncertainty, especially with regard to the upper bound on the 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 clearly indicate that the Baltic is overfished despite the recent increase in spawning stock numbers. The lower bound of the calculated optimal steady-state levels of escapement (233 million individuals) is about 60 percent above the value of 2007 when escapement was 137 million individuals.

Figure 1 about here

We perform the dynamic optimization using the reference parameter set reported in Table 1.¹¹ The resulting optimal developments of the spawning stock and escapement of mature Eastern

¹¹ For the numerical calculation we employed the interior-point algorithm of the Knitro (version 6.0) optimization software with Matlab.

Baltic cod are shown in Figure 1.¹² According to the results, it is optimal to stop harvesting for three years, as in this period optimal escapement equals the spawning stock. After this period, harvesting is gradually increased to the steady-state values.¹³

Figure 2 shows the optimal harvesting fee and the instantaneous profits per unit of harvest at the beginning and at the end of the harvesting seasons. For the transition period of three years, the optimal harvesting fee already exceeds the profit per unit of harvest at the beginning of the season, where harvesting costs are at a minimum, so that no fisherman would have an incentive to start fishing. After the transition period, the harvesting fee and the current profit at the end of the fishing season coincide (cf. condition 5).¹⁴ Overall, the quota price is substantial, with values of almost 60 percent of the ex-vessel price of landed fish.

Figures 2 and 3 about here.

In order to study the sensitivity of optimal dynamics to changes in the parameter values, we perform the dynamic optimization with the two boundary values of the 90% confidence interval of the catchability parameter η (Table 1), while the other parameter values are set as in the reference case. The optimization results are shown in Figure 2. The lower curves, for the

¹² The developments of the stock and escapement of young immature cod are not shown, as over the whole time horizon complete escapement (i.e. zero harvesting) of the young immature cod is optimal.

¹³ The most rapid approach to constant escapement, which would be optimal in the corresponding biomass model with linear objective function (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).

¹⁴ In this period with positive optimal TAC, the price for tradable quotas would be equal to the optimal harvesting fee.

maximum value of catchability parameter, i.e. the case of low harvesting cost, are qualitatively similar to the curves for the reference parameter set shown in Figure 1. However, we observe two quantitative differences: the period of zero harvest lasts only two years, and both the optimal steady-state stock and escapement are considerably lower. Also, steady-state harvest is lower than in the case of the reference parameter set.

In quantitative terms, the upper curves in Figure 3, which display the optimal values for stock and escapement for the minimum value of the catchability parameter (i.e. high harvesting cost) differ from the reference case in that the period of zero harvest is considerably longer (eight years) and their steady-state values are much higher. Steady-state harvest, on the other hand, is lower than in the reference case. In addition, the optimal paths of stock and escapement differ in qualitative terms from the reference case. After the period of zero harvesting, the steady state is approached in damped oscillations with periods of “over-shooting” when stock and escapement exceed the steady-state values.

6. Conclusion and Discussion

In this paper we set up an age-structured fishery model that allows us to distinguish spawning stock and non-spawning stock and to disentangle the problems of recruitment overfishing and growth overfishing. We have shown that, in general, harvest from spawning stock and from non-spawning stock has to be targeted in different ways, meaning that, except from special cases, immature fish and mature fish should be harvested in different quantities. Specifically, we have identified conditions under which it is optimal to harvest mature (spawning) fish only.

Our study provides important policy conclusions. Firstly, 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. For this reason, most fisheries are additionally regulated by gear restrictions (e.g. mesh-size regulations) and minimum landing sizes. We have secondly shown that, although optimal harvesting quantities differ from one age class to another, optimal age-structured management can be implemented by means of setting a single TAC and by issuing or auctioning off tradable harvesting quotas, provided they are specified in terms of the *number* of fish harvested. The quota market will then efficiently allocate the TAC among the different age classes. 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 to the conclusion from the “biomass” model, where the ecological effectiveness of management is guaranteed by setting the appropriate TAC, irrespective of whether quotas are tradable.

A practical implementation of fishery management requires quantifying the TAC or, with the price-based approach, quantifying the harvesting fee. As an illustration we have applied our age-structured model to the Eastern Baltic cod fishery. Here it turns out that the conditions for a zero-harvest policy for immature cod are satisfied. For the older cod, we have computed a time path for total allowable catch that maximizes the present value of resource rents. It involves zero harvesting for a period of three years (due to the linear objective function), then a period of gradually increasing TACs, and ultimately a yearly harvest substantially higher than current harvests. A comprehensive sensitivity analysis shows that current management is clearly not optimal. However, the sensitivity analysis also shows that the quantification of optimal TACs is subject to considerable uncertainty. One conceivable source of uncertainty is that our model is a single species model. Many species, including the Baltic cod, interact with other commercially

valuable species. For example, Baltic cod feeds on sprat and herring, while the sprat feeds on cod eggs and larvae. 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.

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Appendix

A. Derivation of harvesting and profit functions

We assume that instantaneous harvest flows $h_{I,t}(\tau)$ and $h_{M,t}(\tau)$ are determined by current fishing effort $e_{j,t}(\tau)$ targeting age class $j = I, M$ (at time τ) within the fishing season in year t :¹⁵

$$\begin{aligned} h_{I,t}(\tau) &= \eta_I e_{I,t}(\tau) x_{I,t}(\tau)^{\beta} \\ h_{M,t}(\tau) &= \eta_M e_{M,t}(\tau) x_{M,t}(\tau)^{\beta} \end{aligned} \quad (13)$$

Here, $x_{j,t}(\tau)$ is the stock of age $j = I, M$ at time τ , such that $x_{j,t}(\tau) = X_{j,t}$ at the beginning of year t 's fishing season and $x_{j,t}(\tau) = S_{j,t}$ at the end. The parameters $\eta_i > 0$, $i = I, M$, are the catchability coefficients, and $\beta \in (0, 1]$ is the stock elasticity of harvest. Harvesting costs are proportional to effort, with v_j as the unit effort cost. Introducing the cost parameter $c_j = v_j / \eta_j$, the instantaneous profit flows from harvesting these two age classes at time τ within fishing period t are:

$$\begin{aligned} \pi_{I,t}(\tau) &= p_I w_I h_{I,t}(\tau) - c_I x_{I,t}(\tau)^{-\beta} h_{I,t}(\tau) \\ \pi_{M,t}(\tau) &= p_M w_M h_{M,t}(\tau) - c_M x_{M,t}(\tau)^{-\beta} h_{M,t}(\tau). \end{aligned} \quad (14)$$

During the harvesting season, each fish caught diminishes the stock by one unit, i.e. $\dot{x}_{j,t}(\tau) = -h_{j,t}(\tau)$, $j = I, M$. The aggregate annual profit (Π_t) from fishing both age classes in

¹⁵ Alternatively, τ may be interpreted as an index ordering the different fishermen harvesting sequentially.

period t is obtained by integrating the flow of profits over the whole fishing season (see also Clark 1990).

$$\begin{aligned}\Pi_t &= \int_{S_I}^{X_{I,t}} \left[p_I w_I - c_I X_{I,t}^{-\beta} \right] dx_{I,t} + \int_{S_{M,t}}^{X_{M,t}} \left[p_M w_M - c_M X_{M,t}^{-\beta} \right] dx_{M,t} \\ &= p_I w_I \left[X_{I,t} - S_{I,t} \right] - \frac{c_I}{1-\beta} \left[X_{I,t}^{1-\beta} - S_{I,t}^{1-\beta} \right] + p_M w_M \left[X_{M,t} - S_{M,t} \right] - \frac{c_M}{1-\beta} \left[X_{M,t}^{1-\beta} - S_{M,t}^{1-\beta} \right]\end{aligned}\quad (15)$$

The corresponding harvesting function is $H_{M,t} = X_{M,t} - \left[X_{M,t}^{1-\beta} - (1-\beta)\eta_M E_{M,t} \right]^{1/(1-\beta)}$, where $E_{M,t}$ is total effort directed at harvesting age class M in year t . For $\beta = 1$, this equation may be written as $\ln(S_{M,t}) = \ln(X_{M,t}) - \eta_M E_{M,t}$.

B. Steady state conditions and proof of Proposition 3

In a steady state with complete escapement of age class I , i.e. $S_I = X_I$ and partial escapement of age class M , i.e. $0 < S_M < X_M$, the first-order necessary conditions (1.7)-(1.12) imply

$$\begin{aligned}\mu_I &= \lambda_M b_{IM} - \left[p_I w_I - c_I X_I^{-\beta} \right] \\ p_M w_M &= \lambda_M b_{MM} + c_M S_M^{-\beta} \\ \lambda_E &= \rho b_{EJ} \lambda_J = \rho^2 b_{EJ} b_{JI} \lambda_I = \rho^3 b_{EJ} b_{JI} b_{IM} \lambda_M \\ \rho p_M w_M &= \rho c_M X_M^{-\beta} - \rho \lambda_E r'(X_M) + \lambda_M\end{aligned}\quad (16)$$

Combining the last two equations, we can calculate the shadow price λ_M as a function of the spawning stock $\rho p_M w_M = \rho c_M X_M^{-\beta} - \rho^4 r'(X_M) b_{EJ} b_{JI} b_{IM} \lambda_M + \lambda_M$, or:

$$\lambda_M = \rho \frac{p_M w_M - c_M X_M^{-\beta}}{1 - \rho^4 r'(X_M) b_{EJ} b_{JI} b_{IM}}\quad (17)$$

This is the first of two conditions determining the steady state. The other condition is obtained by substituting $X_I = b_{JI} X_J = b_{JI} b_{EJ} X_E = b_{JI} b_{EJ} r(X_M)$ and the second equation of (16) into (2)

$$X_M = b_{IM} b_{JI} b_{EJ} r(X_M) + b_{MM} \left[\frac{c_M}{p_M w_M - \lambda_M b_{MM}} \right]^{\frac{1}{\beta}} \quad (18)$$

To prove the proposition, we now show that $\mu_I > 0$ provided that $c_I \geq c_M$ and condition (11) hold. Substituting (17) into (16) (first equation), we obtain

$$\begin{aligned} \mu_M &= \rho \frac{p_M w_M - c_M X_M^{-\beta}}{1 - \rho^4 r'(X_M) b_{EJ} b_{JI} b_{IM}} b_{IM} - \left[p_I w_I - c_I X_I^{-\beta} \right] \\ &> b_{IM} \rho \left[p_M w_M - c_M X_M^{-\beta} \right] - \left[p_I w_I - c_I X_I^{-\beta} \right] \\ &> c_I X_I^{-\beta} - b_{IM} \rho c_M X_M^{-\beta} \geq c_M \left[X_I^{-\beta} - b_{IM} \rho X_M^{-\beta} \right] \\ &= c_M \left[X_I^{-\beta} - b_{IM} \rho b_{IM} X_I + b_{MM} S_M^{-\beta} \right] \\ &\geq c_M \left[X_I^{-\beta} - b_{IM}^{1-\beta} \rho X_I^{-\beta} \right] = c_M X_I^{-\beta} \left[1 - b_{IM}^{1-\beta} \rho \right] > 0 \end{aligned} \quad (19)$$

C. Proof of Proposition 5

We consider one representative fisherman harvesting age class $j = I, M$ who chooses the quota H_j at a quota price ψ_t (which is independent of j) such as to maximize

$$\max_{H_{j,t}} \left\{ p_j w_j H_{j,t} - \frac{c_j}{1-\beta} \left[X_{j,t}^{1-\beta} - \left[X_{t,j} - H_{j,t} \right]^{1-\beta} \right] - \psi_t H_{j,t} \right\} \quad (20)$$

The first-order conditions of profit maximization are

$$p_j w_j - c_j \left[X_{j,t} - H_{j,t} \right]^{-\beta} \leq \psi_t \quad (21)$$

with equality for $H_{j,t} > 0$. Comparison with the first-order conditions for the social optimum, (5)

and (6), yields that the quota price is $\psi_t = b_{23} \lambda_{3,t} = b_{33} \lambda_{3,t}$ if $H_{j,t} = X_{j,t} - S_{j,t}$, $j = I, M$, i.e. if the quota market clears.

D. Estimation of cost parameters

Effort is measured in days at sea. The variable costs of fishing per day at sea are calculated according to Kronbak (2002). Data is available for fishing vessels operating in the region of Bornholm, a major fishing area in the Eastern Baltic Sea, for the years 1996-2007 from the Fiskeriregnskabsstatistik (2007). To obtain the variable cost per day at sea in Danish Crowns (DKK), the variable cost of harvesting cod are divided by the days at sea a firm is harvesting cod in the Bornholm region. The variable cost of harvesting cod are obtained as the product of variable cost (in 1000 DKK per firm) and the share of cod expressed through the quotient of gross output in the cod fishery and gross output in total. The variable costs are derived adding labor cost of fishermen and total cost (in 1000 DKK per firm) and subtracting depreciation. Specifically, we use the following data and calculations, here illustrated for data from 2007.

A) Gross Output for cod, 1000 DKK/firm	1201
B) Gross Output in Total; 1000kr/firm	1782
C) Share of cod (equal to A/B);	0.67
D) Total cost, 1000 DKK/firm	1240
E) Total cost of hired labor, 1000DKK/firm	383
F) Depreciation, 1000 DKK/firm	160
G) Labor input of crew, Days at sea/firm	178
H) Labor input of fisherman, Days at sea/firm	110

I) Wage per day (equal to E/G)	2.15
J) Labor cost of fisherman, 1000DKK/firm (equal to I*H)	236.68
K) Variable cost, 1000DKK/firm (equal to J+D-F)	1316.69
L) Variable cost of cod, 1000DKK/firm (equal to K*C)	882.18
M) Days at sea harvesting cod per firm	120
N) Variable cost per day, DKK. (equal to L/M*1000)	7351.5

With an average price in 2007 of 13.36 DKK/kg, we find $\nu^{2007} = 0.550$ tons/day. The overall figure of $\nu = 0.554$ is obtained as the average over the estimates for 1995 to 2007. For the years 1995-1999 we used the estimations of Kronbak (2002), while for the years 2000-2007 we calculated the cost/price ratio with the method described above using data from Fiskeriregnskabsstatistik (2007). The minimum estimated cost/price ratio was $\nu^{2002} = 0.277$ in 2002, the maximum was $\nu^{1996} = 1.404$ in 1996. The standard deviation of cost/price ratios is 0.305, leading to a 90% confidence interval of [0.414,0.693].

Parameter	Sy mbol	Value	Confidence interval
Survival rate eggs – age 1	b_{EJ}	1	
Survival rate age 1 – age 2	b_{JI}	1	
Survival rate age 2 – age 3	b_{IM}	0.81	
Survival rate age 3 – age 3	b_{MM}	0.82	
Weight at age 2	w_I	0.44 kg/fish	
Weight at age 3	w_M	0.96 kg/fish	
Parameter function	recruitment	γ_1	1.54 [1.17,2.02]
Parameter function	recruitment	γ_2	$1.5 \cdot 10^{-9}$ /fish [0.47 $\cdot 10^{-6}$, 2.53 $\cdot 10^{-9}$]
Stock elasticity of harvest	β	1	
Catchability coefficient	η	$2.08 \cdot 10^{-6}$ ton s/day	[0.64 $\cdot 10^{-6}$, 3.51 $\cdot 10^{-6}$]
Ex-vessel price	p_I =	1	
Cost/price ratio	ν	0.55 tons/day	[0.41,0.69]
Discount factor	ρ	0.95	[0.90,1.0]

Table 1: Estimated parameters and confidence intervals (90%, where applicable). Sources and methods are described in the text.

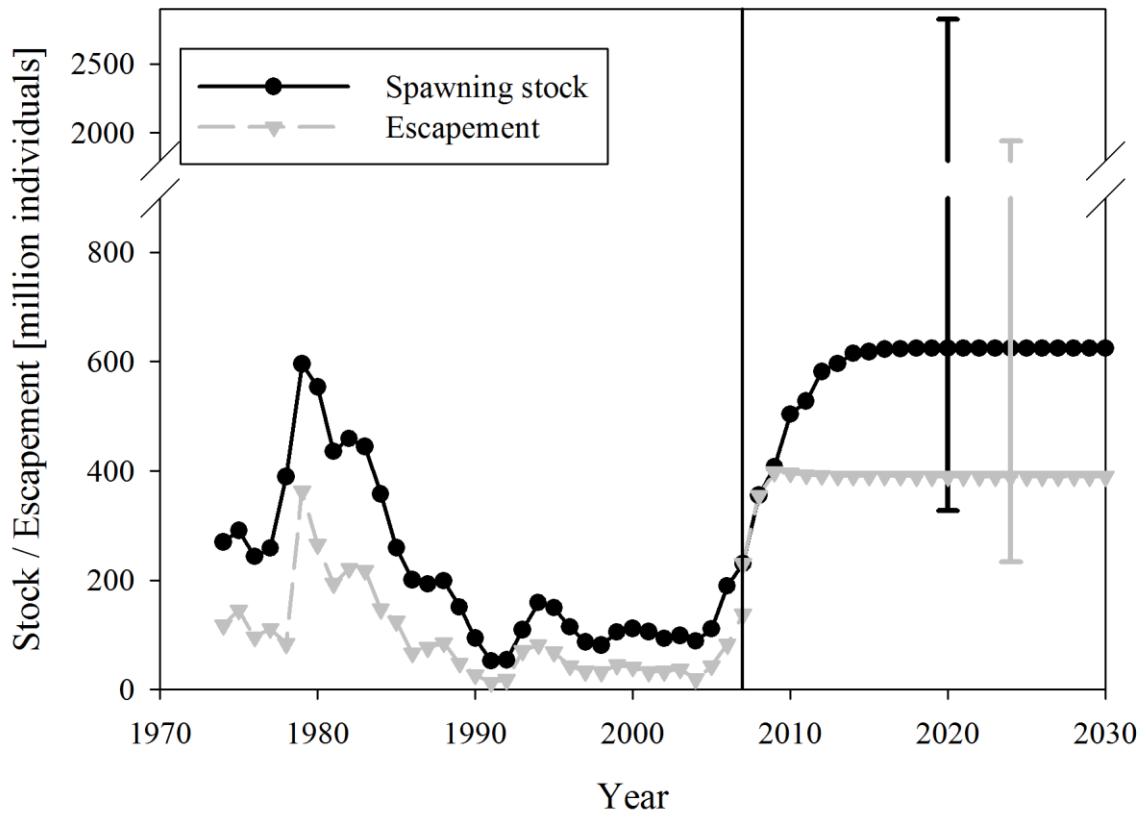


Figure 1: Spawning stock and escapement of Eastern Baltic cod. ICES data from 1974-2007, results of numerical optimization from 2007 to 2030. Parameter values are given in Table 1.

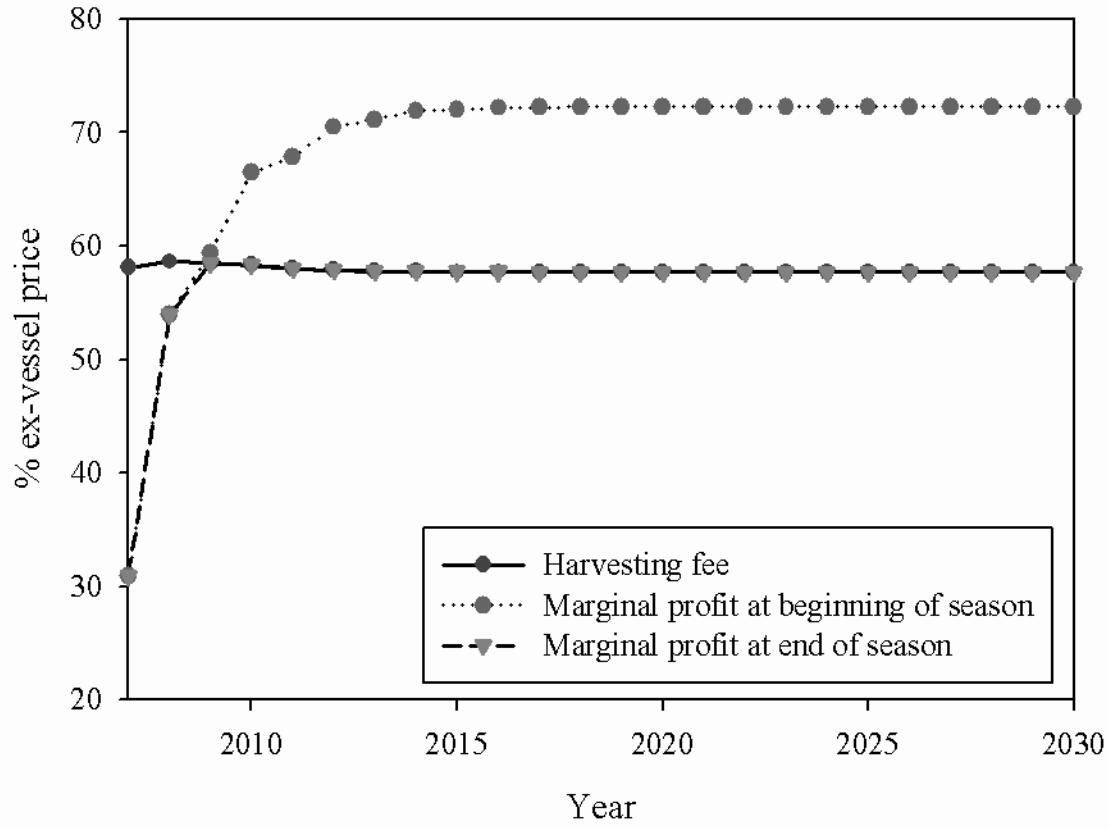


Figure 2: Harvesting fee and instantaneous profit at beginning and end of fishing seasons, for the optimal management under the reference parameter set.

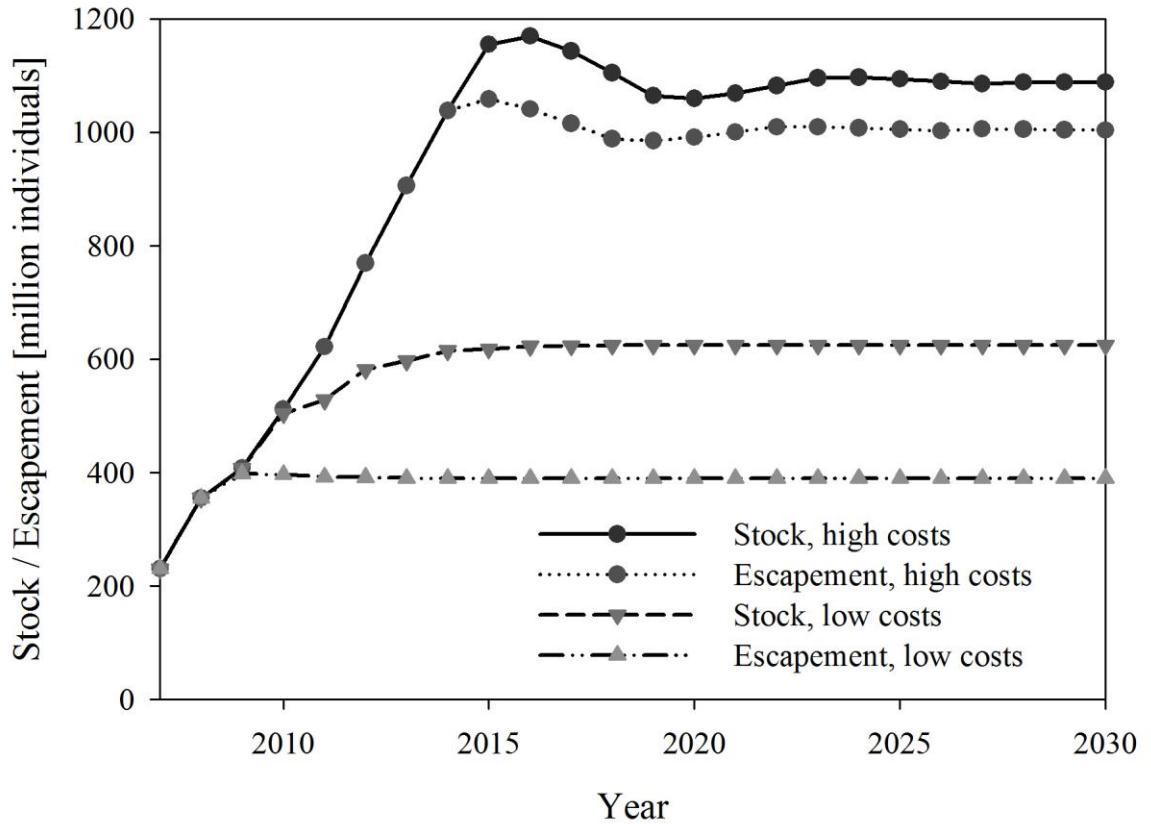


Figure 3: Sensitivity analysis of optimal dynamics. The upper curves show the result for the minimum, the lower curves for the maximum catchability coefficient out of the 90% confidence interval reported in Table 1. The other parameters are as in Figure 1.