Numbers vs. biomass: Second-best quota management for age-structured fisheries

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Abstract

Fisheries are often managed by harvest quotas and additional gear restrictions to protect young fish. We study the idea to deregulate fishing gear choice, leaving fishing quotas as the only instrument of the regulator. In this second-best setting, we study a simple change of "currency" for individual fishing quotas: Measuring quotas in terms of numbers rather than in terms of biomass could improve the incentives to target larger fish, thus solving the persistent growth overfishing problem without gear restrictions. The intuition is clear: A fisher has much stronger incentives to select for large fish when she or he has the right to catch a number x of individual fish, rather than x tons of fish. We theoretically derive conditions under which this simple change in the type of quotas leads to welfare gains. We find that the age-dependence of prices, fish weights and natural mortality rates all play a role in determining whether biomass quotas outperform number quotas. We then quantify the effect of biomass and number quotas in an age-structured bio-economic model for the Eastern Baltic Cod trawl fishery. We find that steady-state profits under second-best number-quota management are only 0.5% below the first-best.

Keywords: Fisheries management, Bio-economics, Growth overfishing

JEL Codes: Q22, Q28

1 Introduction

Fisheries have the potential to provide food and livelihood for millions of people (Smith et al. 2010). After a long history of over-exploitation (Worm et al. 2006), the indicators of many assessed fish stocks have been improving in recent years (Costello et al. 2012). However, the age- and size-structure of these resources has often been severely distorted. The systematic removal of fish before they have grown old and large (growth overfishing) may have destabilizing, and potentially irreversible, consequences (Anderson et al. 2008, Stenseth and Rouyer 2008). Finding ways to correct for the incentives of growth overfishing is therefore of immediate policy relevance.

It is clear that undifferentiated biomass quotas will not be able to solve the problem of growth overfishing (Costello and Deacon 2007, Diekert 2012, Quaas et al. 2013). As fully delineating quotas is prohibitively costly, individual fishing quotas are often coupled with gear restrictions aimed at protecting small fish. Typical measures include minimum size limits and minimum mesh sizes. Given that individual fishing quotas have many desirable properties that rendered previous command and control measures such as season length restrictions unnecessary, we analyze the need for gear restrictions in a deregulated second-best setting: While the regulator sets the annual fishing quota, the fishermen are free to select the target fish size. In this second-best setting, we study if measuring quotas in terms of numbers (instead of in terms of biomass what is currently the predominant practice) could considerably improve the incentives for not selecting age groups that are too young and small. The intuition is clear: A fisher has much stronger incentives to select for large fish when she or he has the right to catch a number x of individual fish, rather than x tons of fish.

We set up a simple theoretical model of an age-structured fishery to show that is intuition is correct, but may be misleading: In some cases, a biomass quota is actually more efficient than a number quota. Given the lack of a general ranking of these instruments, it is an empirical question which is the superior one. We thus quantify the welfare effect of either management approach for the Baltic cod trawl fishery. For this fishery, the second-best regulation by means of number quotas comes very close to the first-best outcome in steady state, with some efficiency losses in the transition period. The second-best biomass quota management performs worse than the second-best number quota management, but also leads to a fairly efficient steady state with only about 4% efficiency losses compared to the first best. The reason is that for Baltic Cod, fish prices strongly increase with the size of individual fish.

Our paper contributes to the growing literature on age-structured modeling in fisheries, pioneered by Tahvonen (2009). With the exception of Diekert (2012), Quaas et al. (2013), this literature has been focusing on optimal fishery management. We extent this state-of-the art in methodical terms by considering the strategic interaction between the regulator of the fishery – who sets the fishing quotas – and fishermen – who choose mesh sizes.

To influence this strategic interaction, we propose the introduction of number quotas. Although the idea of "changing the currency" is conceptually simple, assessing its welfare effects requires a detailed age-structured bio-economic model.

The paper proceeds as follows: In section 2, we provide the simplest possible characterization of an age-structured fishery to discuss the main underlying forces that determine when management with quotas in terms of numbers and/or biomass can achieve the first-best and when not. We then extend this model to account for stock-dependent harvesting costs and imperfect selectivity in section 3. Throughout section 3, we illustrate our theoretical findings using an empirical model of the Eastern Baltic Cod trawl fishery. Section 4 concludes the paper with a discussion of the results.

2 Simple two age-class model

Throughout this section, we first describe the socially optimal harvesting pattern and then study the efficiency of biomass- or number-based quota management approaches when fishermen choose fishing gear such as to maximize their current profit. To highlight the key underlying factors that determine the harvesting pattern, we use the most simple age-structured model, considering two age classes only. We assume perfect selectivity and abstract from harvesting costs (or assume that harvesting cost do not depend on stock size or gear selectivity).

Let x_{it} denote the stock number of age-group i in period t, w_i weight-at-age, p_i the ex-vessel price per kilogram of fish and h_{it} the number of fish that are harvested. Let α_i be the natural survival rate of fish that have not been harvested in period t. The number of fish in age class 2 at the beginning of period $t+1$ follows as the number of fish in age class 1 that have not been harvested in period t and that have survived natural mortality, $\alpha_1 (x_{1t} - h_{1t})$, plus the fish that stay in age class 2:

$$x_{2,t+1} = \alpha_1 (x_{1t} - h_{1t}) + \alpha_2 (x_{2t} - h_{2t}) \tag{1}$$

Using $\varphi(\cdot)$ to denote the stock-recruitment function and γ_i to denote maturity-at-age, recruitment into age class 1 can be described as

$$x_{1,t+1} = \varphi(\gamma_1 \, x_{1t} + \gamma_2 \, x_{2t}) \tag{2}$$

As fish don't shrink, we have $w_2 > w_1$. Furthermore, we assume that $p_1 \neq p_2$, $p_1 w_1 \neq p_2 w_2$ and $\frac{p_1 w_1}{\alpha_1} \neq \frac{p_2 w_2}{\alpha_2}$ to avoid tedious boundary cases. In most cases, we have $p_1 < p_2$ (Asche et al. 2015, Zimmermann and Heino 2013). Still, the case $p_1 > p_2$ may be explained by price reductions for larger fish if their processing is costlier than that of smaller fish (in case smaller fish are common, i.e. if the fish processing industry has adapted to persistent growth overfishing) or if toxins accumulate in the fish during their life span.

First-best management

The Lagrangian for the problem to maximize the present value of revenues, using a discount factor $0 < b < 1$, is given by

$$L = \sum_{t=0}^{\infty} b^t \Big\{ p_1 \, w_1 \, h_{1t} + p_2 \, w_2 \, h_{2t} + \lambda_t \, \left(\alpha_1 \left(\varphi(\gamma_1 \, x_{1t} + \gamma_2 \, x_{2t}) - x_{1,t+1}\right)\right. \\ \left. + \, \mu_t \, \left(\alpha_1 \left(x_{1t} - h_{1t}\right) + \alpha_2 \left(x_{2t} - h_{2t}\right) - x_{2,t+1}\right) \Big\} \tag{3}$$

The first-order conditions for the optimal catch numbers h^*_{1t}, h^*_{2t} are

$$h_{1t} \frac{\partial L}{\partial h_{1t}} = 0 \qquad \text{and} \qquad \frac{\partial L}{\partial h_{1t}} = p_1 \, w_1 - \mu_t \, \alpha_1 \leq 0 \tag{4}$$

$$h_{2t} \frac{\partial L}{\partial h_{2t}} = 0 \qquad \text{and} \qquad \frac{\partial L}{\partial h_{2t}} = p_2 \, w_2 - \mu_t \, \alpha_2 \leq 0 \tag{5}$$

From (4) and (5), we conclude that the solution pattern for optimal harvesting is:

$$h^*_{1t} > 0, \quad h^*_{2t} = 0 \quad \text{if} \quad p_1 \, w_1/\alpha_1 > p_2 \, w_2/\alpha_2 \tag{6}$$

$$h^*_{1t} = 0, \quad h^*_{2t} > 0 \quad \text{if} \quad p_1 \, w_1/\alpha_1 < p_2 \, w_2/\alpha_2 \tag{7}$$

The exact values for h^*_{1t} in the first case, and for h^*_{2t} in the second case, depend on all first-order conditions listed in Appendix A. Here, we are solely interested in the selectivity pattern. The term $p_i \, w_i/\alpha_i$ can be called the "mortality adjusted biovalue" of age group i and clearly, the age group with the higher mortality adjusted biovalue should be harvested. The intuition is the following:

When the survival rate of age-group 1 is the same as the survival rate of age group 2, and prices are approximately equal, too, it is best to harvest the heavier individuals. Conversely, when the weight are approximately equal and survival rates identical, it is best to harvest individuals of the age-class that obtains the higher price. When the biovalue ($p_i\, w_i$) of the two age groups the same (when all prices and weights are equal, or when the amount by which age group 2 is heavier than age group 1 is exactly canceled by the price differential between age group 1 and age group 2) , we should harvest the age-group with the lower survival rate (lower α_i), simply because it will succumb to natural mortality otherwise.

Management with individual quotas

Consider many fishermen who maximize short-run profits subject to an individual quota Q^z. The quota can either be measured in terms of biomass, e.g. in kilograms of fish, or in terms of the number of fish caught:

$$Q^z \text{ with } \quad z \in \begin{Bmatrix} B & \text{catch measured in biomass,} \\ H & \text{catch measured in number of fish} \end{Bmatrix} \tag{8}$$

Consider first the case of a biomass quota Q^B. The problem of a representative fisherman is:

$$\begin{aligned} \max_{h_{1t},h_{2t}} \{p_1\, w_1\, h_{1t} + p_2\, w_2\, h_{2t}\} \qquad \text{subject to} \quad & w_1\, h_{1t} + w_2\, h_{2t} \leq Q^B \\ = & \max_{h_{1t}} \left\{p_1\, w_1\, h_{1t} + p_2\, (Q^B - w_1\, h_{1t})\right\} \end{aligned} \tag{9}$$

and the solution is:

$$h_{1t} = \frac{Q^B}{w_1}, \quad h_{2t} = 0 \quad \text{if} \quad p_1 > p_2 \tag{10}$$

$$h_{1t} = 0, \quad h_{2t} = \frac{Q^B}{w_2} \quad \text{if} \quad p_1 < p_2 \tag{11}$$

Now consider the problem of a representative fisherman with a number quota Q^N:

$$\begin{aligned} \max_{h_{1t},h_{2t}} \{p_1\, w_1\, h_{1t} + p_2\, w_2\, h_{2t}\} \text{ subject to } & h_{1t} + h_{2t} \leq Q^N \\ = & \max_{h_{1t}} \left\{p_1\, w_1\, h_{1t} + p_2\, w_2\, (Q^N - h_{1t})\right\} \end{aligned} \tag{12}$$

Under this management regime, the fisher will choose:

$$h_{1t} = Q^N, \quad h_{2t} = 0 \quad \text{if} \quad p_1\, w_1 > p_2\, w_2 \tag{13}$$
$$h_{1t} = 0, \quad h_{2t} = Q^N \quad \text{if} \quad p_1\, w_1 < p_2\, w_2 \tag{14}$$

We can now characterize the different ways to measure quotas (using $\text{sgn}\{x\}$ to denote the sign of x).

Proposition 1. *For the simple two-age-class model without fishing costs and with perfect selectivity,*

- *both biomass quotas and number quotas can implement first best if:*

$$sgn\{p_1 - p_2\} = sgn\{p_1\, w_1 - p_2\, w_2\} = sgn\{p_1\, w_1/\alpha_1 - p_2\, w_2/\alpha_2\}\,. \tag{15}$$

- *number quotas are better than biomass quotas (and implement first best) if*

$$sgn\{p_1 - p_2\} \neq sgn\{p_1\, w_1 - p_2\, w_2\} = sgn\{p_1\, w_1/\alpha_1 - p_2\, w_2/\alpha_2\}\,. \tag{16}$$

- *biomass quotas are better than number quotas (and implement first best) if*

$$sgn\{p_1\, w_1 - p_2\, w_2\} \neq sgn\{p_1 - p_2\} = sgn\{p_1\, w_1/\alpha_1 - p_2\, w_2/\alpha_2\}\,. \tag{17}$$

- *neither instrument can implement first best, not even in this very simple model, if*

$$sgn\{p_1 - p_2\} = sgn\{p_1\, w_1 - p_2\, w_2\} \neq sgn\{p_1\, w_1/\alpha_1 - p_2\, w_2/\alpha_2\}\,. \tag{18}$$

Proof. Follows directly from combining (6)-(7) with (10)-(11) and (13)-(14). □

Intuitively, when the fishermen have opportunity costs for every kilogram they harvest, they are only interested in the relative price per kg. When they have opportunity costs per harvested individual, they care both about the price and the weight per individual (the biovalue). The social planner, however, takes the full (shadow) price into account by also considering the relative survival rates of both age classes (the mortality adjusted biovalue).

We presented this simple model to underline that no quota measure outperforms the other quota measure a priori. If one excludes the possibility of $p_2 < p_1$, the incentives of fishermen with number or biomass quotas align in our simple model. Their common interest in catching the larger fish may vanish if one takes imperfect selectivity and stock-dependent fishing costs into account. This is done in the following section.

3 Model with imperfect selectivity and fishing costs

Actual fishing gear selects for size groups only imperfectly. This imperfect selectivity renders it impossible for the fisherman to exactly choose the number of fish he wants to remove from each age class. We model imperfect selectivity by assuming that the fisherman can only adjust his fishing effort E_t and the mesh size σ_t of his fishing net.

Let $q_i(\sigma_t) \in [0, 1]$ denote the retention probability of a fish of age i entering a net with mesh size σ_t. The larger the mesh size, the lower the probability that a fish entering the net is caught, $q_i'(\cdot) < 0$, $\lim_{\sigma_t \to 0} q_i(\sigma_t) = 1$, $\lim_{\sigma_t \to \infty} q_i(\sigma_t) = 0$. We have depicted exemplary retention probability curves from our empirical example of the Eastern Baltic Cod trawl fishery in Figure 1.

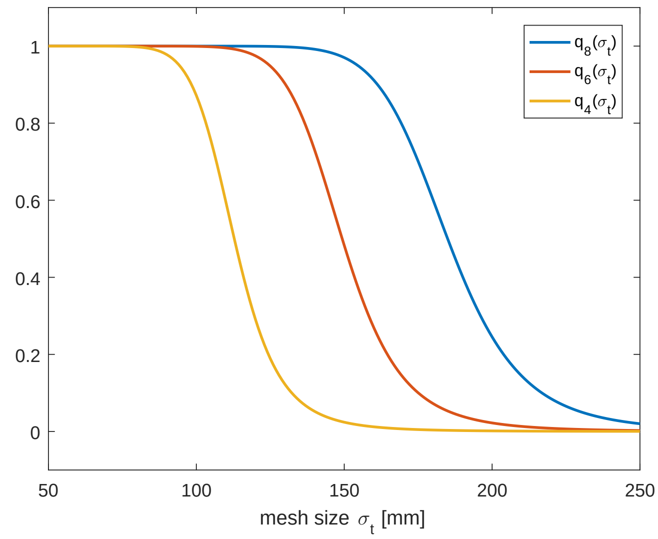

Figure 1: Retention probabilities of Eastern Baltic Cod age $i = 4, 6, 8$ entering a trawl net with mesh size σ_t.

The total actual catch H_t^z can either be measured in total biomass caught ($z = B$) or in the total number of fish caught ($z = N$),

$$H_t^z \text{ with } \quad z \in \left\{ \begin{array}{ll} B & \text{catch measured in biomass,} \\ H & \text{catch measured in number of fish} \end{array} \right\} \tag{19}$$

For fishing with mesh size σ_t we assume that the age-composition in catch equals the age-composition of all fish in the stock that are vulnerable to fishing with σ_t. The underlying basic assumption is that the fish age distribution is equal across all fish accumulations within the geographic range of the stock. Following this assumption, fishing location choice has no effect on the age-composition in catch. This assumption underestimates the capabilities of fishermen to influence fishing selectivity. Modeling fishing selectivity as being influenced by both fishing location choice and fishing gear choice would require a spatially explicit dynamic model. This is beyond the scope of this paper, however. Instead, we focus on fishing gear choice as it is the margin that is predominantly regulated in actual fisheries management. The assumption that the age-composition in catch equals the age-composition of all fish vulnerable at mesh size σ_t can either be formulated in biomass or in number terms:

$$\frac{h_{jt}}{H_t^N} = \frac{q_j(\sigma_t)\, x_{jt}}{\sum_{i=1}^n q_i(\sigma_t)\, x_{it}} \tag{20}$$

$$\frac{w_j h_{jt}}{H_t^B} = \frac{w_j\, q_j(\sigma_t)\, x_{it}}{\sum_{i=1}^n w_i\, q_i(\sigma_t)\, x_{it}} \tag{21}$$

Equations (20) and (21) are equivalent representations of the above mentioned assumption. Tahvonen et al. (2016) denote the part of the total stock biomass that is vulnerable to fishing the "efficient biomass" $B_t(\sigma_t, \mathbf{x_t})$,

$$B_t(\sigma_t, \mathbf{x_t}) = \sum_{i=1}^{n} w_i\, q_i(\sigma_t)\, x_{it}. \tag{22}$$

Following the same idea, let $N_t(\sigma_t)$ denote the "efficient stock size", i.e. the number of fish that are vulnerable to fishing with with mesh size σ_t:

$$N_t(\sigma_t, \mathbf{x_t}) = \sum_{i=1}^{n} q_i(\sigma_t)\, x_{it} \tag{23}$$

Combining (20) and (21) yields a conversion rule for the two catch measures

$$\frac{H_t^B}{B_t(\sigma_t)} = \frac{H_t^N}{N_t(\sigma_t)} \tag{24}$$

To simplify notation in the following, both sides of equation (24) can be written in standardized catch units

$$\omega^z(\sigma_t, \mathbf{x_t})\, H_t^z \quad \text{with} \quad \omega_z(\sigma_t) = \begin{cases} B(\sigma_t)^{-1} & \text{if } z = B \\ N(\sigma_t)^{-1} & \text{if } z = N \end{cases} \tag{25}$$

From (20), (21), (24) and (25) follows for the number of fish caught from age class i:

$$h_{it} = q_i(\sigma_t)\, x_{it}\, \omega_z(\sigma_t)\, H_t^z \tag{26}$$

A standard assumption in fisheries economics is that fishing costs are linear in catch. With exogenous landing prices, it follows that fishing revenues are linear in catch as well. Using (24), fishing profits can thus be written as a linear function of standardized catch

$$\Pi_t(\sigma_t, H_t^z) = \pi_t(\sigma_t)\, \omega_z(\sigma_t)\, H_t^z \tag{27}$$

The term $\pi_t(\sigma_t)$ can be interpreted as the marginal and average revenue of one unit of the standardized catch measure $\omega_z(\sigma_t)\, H_t^z$.

First-best management

To prevent unrealistic pulse fishing solutions in the first-best case, we insert the annual profits from fishing into a concave positive monotone transformation $g(\cdot)$ with $g'(\cdot) > 0, g''(\cdot) < 0$.

The optimization problem of social planner follows as:

$$\begin{aligned}
\max_{(H_t^z)_{t=1}^{\infty}, (\sigma_t)_{t=1}^{\infty}} L = \sum_{t=1}^{\infty} b^t \Bigg\{ & g\Bigg(\Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\, \omega_z(\sigma_t)\, H_t^z\Bigg) \\
& - \lambda_{0,t}\Big[x_{1,t+1} - \varphi(\mathbf{x}_t)\Big] \\
& - \sum_{i=1}^{n-2} \lambda_{it}\Big[x_{i+1,t+1} - \alpha_i\,(1 - q_i(\sigma_t)\, \omega_z(\sigma_t)\, H_t^z)\, x_{it}\Big] \\
& - \lambda_{n-1t}\Big[x_{n,t+1} - \alpha_{n-1}\,(1 - q_{n-1}(\sigma_t)\, \omega_z(\sigma_t)\, H_t^z)\, x_{n-1t} \\
& \qquad - \alpha_n\,(1 - q_n(\sigma_t)\, \omega_z(\sigma_t)\, H_t^z)\, x_{n,t}\Big]\Bigg\}
\end{aligned} \tag{28}$$

To simplify notation, we have reformulated (28) using $\lambda_{nt} \equiv \lambda_{n-1t}$ (see Appendix B). For $H_t^z > 0$, $g'(\cdot) \neq 0$, a necessary condition for the first-best mesh size in period t can be written as

$$\Big(r_t'(\sigma_t) - c_t'(\sigma_t) - s_t'(\sigma_t)/g'(\cdot)\Big)\omega_z(\sigma_t) + \Big(r_t(\sigma_t) - c_t(\sigma_t) - s_t(\sigma_t)/g'(\cdot)\Big)\omega_z'(\sigma_t) = 0, \tag{29}$$

where we have defined $s_t(\sigma_t) = \sum_{i=1}^{n} \lambda_{it}\,\alpha_i\,q_i(\sigma_t)\,x_{it}$, which is the value of efficient biomass in stock.

We use the Eastern Baltic Cod trawl fishery as our empirical example as extensive gear selectivity experiments have been carried out in this fishery (Madsen 2007). Eastern Baltic Cod is the largest cod stock in the Baltic Sea and trawling the most important gear type. The details of our numerical model can be found in Appendix D.

Using the AMPL software package (Fourer et al. 2009), we solve the first-best optimization problem (28) numerically. The starting year of our computations is 2013. The results are summarized in Figure 2. These results are similar to those of Tahvonen

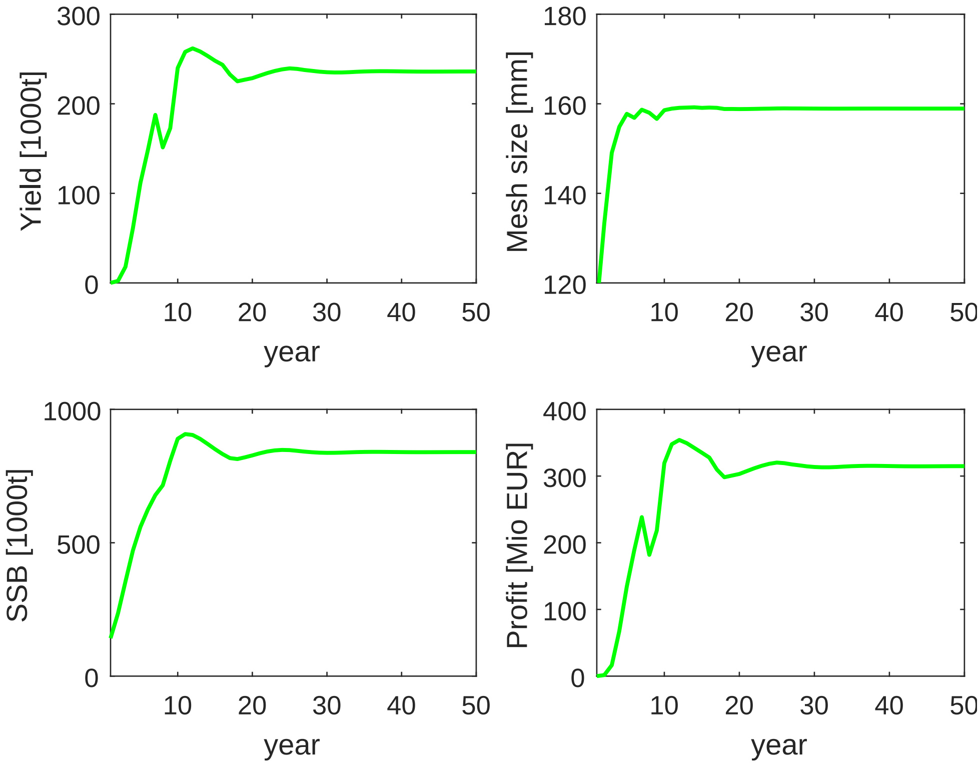

Figure 2: First-best management of Eastern Baltic Cod.

et al. (2016) except for the optimal mesh size. The lower optimal mesh size reported by Tahvonen et al. (2016) is most likely due to their inverse demand function not depending on fish size.

Management with individual quotas

As in our simple model, each fisherman is regulated by an individual quota Q_t^z. The fisherman observes Q_t^z and adjusts mesh size σ_t and actual annual catch H_t^z myopically in each period t. His static optimization problem follows as:

$$\begin{aligned} \max_{\sigma_t, H_t^z} \quad & \Pi_t = \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\, \omega_z(\sigma_t)\, H_t^z \\ \text{s.t.} \quad & H_t^z \leq Q_t^z \end{aligned} \tag{30}$$

Whenever there exists a mesh size that yields a positive marginal profit per unit of catch, $(r_t(\sigma_t) - c_t(\sigma_t))\, \omega_z(\sigma_t) > 0$, the quota constraint becomes binding. The mesh size $\tilde{\sigma}_t$ that delivers the most profitable catch composition to deplete the quota follows as (cf. Appendix C)

$$\Big(r_t'(\tilde{\sigma}_t) - c_t'(\tilde{\sigma}_t)\Big)\omega_z(\tilde{\sigma}_t) + \Big(r_t(\tilde{\sigma}_t) - c_t(\tilde{\sigma}_t)\Big)\omega_z^{'}(\tilde{\sigma}_t) = 0 \tag{31}$$

Comparison of (31) with the first-best mesh size condition (29) illustrates that the fisherman disregards the effect of his mesh size choice onto future periods. The fraction of each age class that survives natural mortality and is vulnerable to fishing with mesh size σ_t, $\alpha_i\, q_i(\sigma_t)\, x_{it}$, is valued by the social planner by its shadow price, λ_{it}. The effect of the mesh size onto the aggregated shadow value $s_t(\sigma_t) = \sum_{i=1}^{n} \lambda_{it}\, \alpha_i\, q_i(\sigma_t)\, x_{it}$ is absent in eq. (31).

To depict the fishermen incentives under biomass quotas and number quotas, we consider the solution of (31) for the example of the Eastern Baltic Cod trawl fishery in Figure 3. The leftmost points on the y-axis depict the preferred mesh sizes of fishermen targeting the fish stock in year 2013 (the starting point of our simulations). Fishermen having biomass quotas would use $\sigma_1 = 84$ mm whereas fishermen having number quotas would use $\sigma_1 = 122$ mm.

The solid lines indicate the preferred mesh sizes if additional fish of age $i = 8$ would be added to the stock in year 2013, holding all other age classes constant. Using dashed lines (dotted lines), the same idea of comparative statics is applied to show the effect of increasing the number of fish in age class 7 (age class 6), holding all other age classes constant. Interestingly, Figure 3 shows that the minimum mesh size regulation (EC 2010) is binding under the current system of biomass quotas. Under number quotas, this would not be the case.

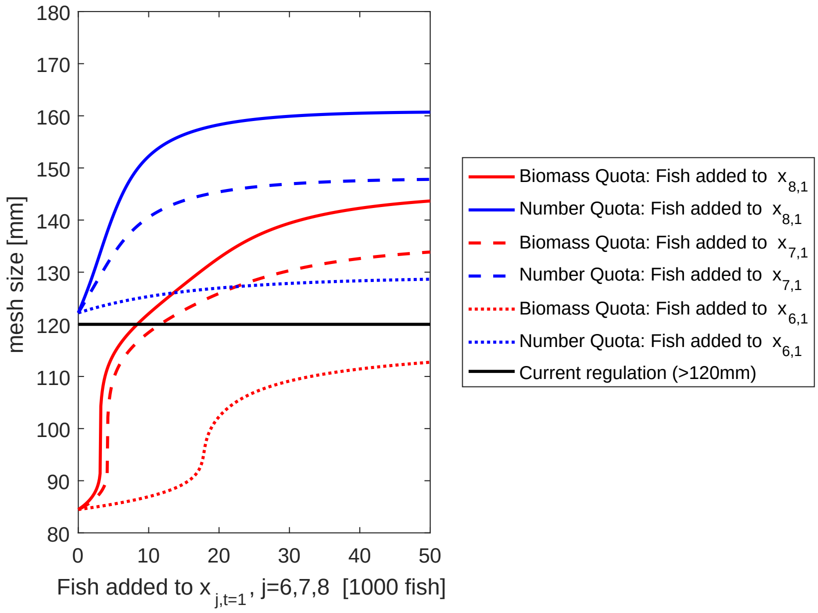

Figure 3: Optimal mesh sizes for fishermen with biomass quotas (red) or number quotas (blue) and more fish added relative to x_{1t}.

Second-best management with individual quotas

If mesh size is deregulated, the social planner has to anticipate the mesh size optimization carried by fishermen in every period t when calculating the second-best quota trajectory $(Q_t^z)_{t=1}^{\infty}$. This bilevel optimization problem can be simplified by using the first-order condition (31) from the lower-level optimization problem of the fisherman as a constraint in the upper-level second-best optimization problem of the social planner:

$$\begin{aligned}\max_{(Q_t^z)_{t=1}^{\infty},(\sigma_t)_{t=1}^{\infty}} L = \sum_{t=1}^{\infty} b^t \Bigg\{ & g\Bigg(\Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\,\omega_z(\sigma_t)\,Q_t^z\Bigg) \\ & - \lambda_{0,t}\Big[x_{1,t+1} - \varphi(\mathbf{x}_t)\Big] \\ & - \sum_{i=1}^{n-2} \lambda_{it}\Big[x_{i+1,t+1} - \alpha_i\left(1 - q_i(\sigma_t)\,\omega_z(\sigma_t)\,Q_t^z\right) x_{it}\Big] \\ & - \lambda_{n-1t}\Big[x_{n,t+1} - \alpha_{n-1}\left(1 - q_{n-1}(\sigma_t)\,\omega_z(\sigma_t)\,Q_t^z\right) x_{n-1t} \\ & \qquad - \alpha_n\left(1 - q_n(\sigma_t)\,\omega_z(\sigma_t)\,Q_t^z\right) x_{n,t}\Big] \\ & + \mu_t\Bigg[\Bigg(\Big(r_t'(\sigma_t) - c_t'(\sigma_t)\Big)\omega_z(\sigma_t) + \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\omega_z'(\sigma_t)\Bigg)\; Q_t^z\Bigg]\Bigg\},\end{aligned} \tag{32}$$

where the last line of (32) requires (31) to hold only for $Q^z_t > 0$.

For our example of the Eastern Baltic Cod trawl fishery, we have plotted the second-best values relative to their first-best levels in Figure 4. A comparison of the steady-state

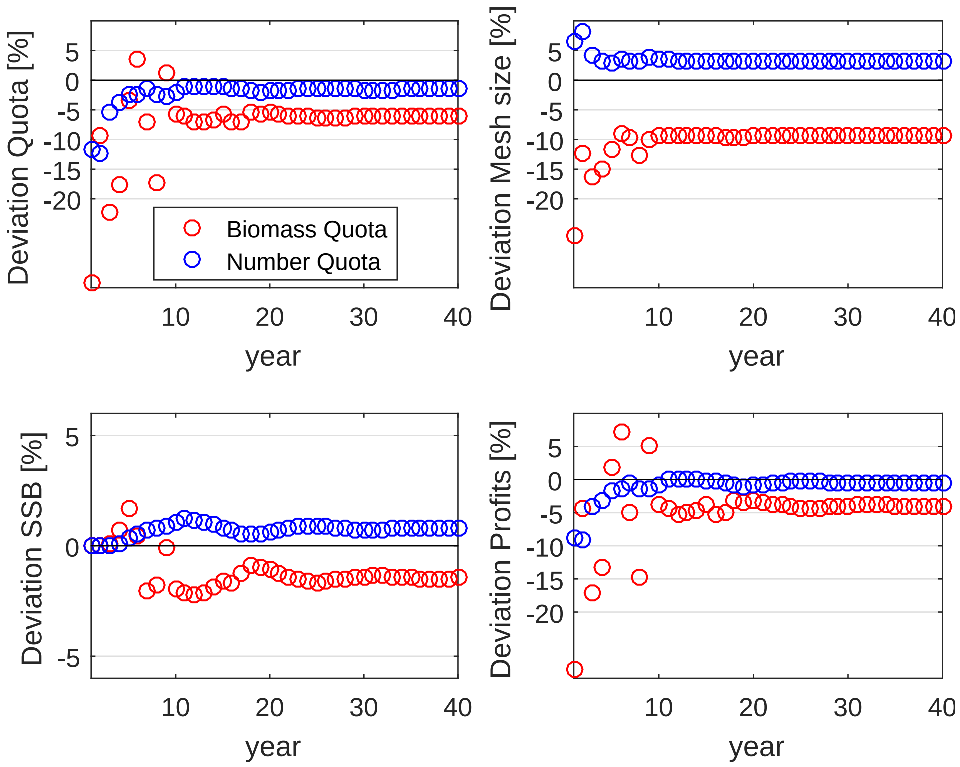

Figure 4: Deviations relative to first-best management: Second-best management with biomass quotas (red circles) and number quotas (blue circles).

levels reveals that the spawning stock sizes are nearly equal: The second-best stock size with biomass quotas (number quotas) deviates from the first-best by -1.5% ($+0.8\%$). At comparable stock sizes, fishermen with biomass quotas (number quotas) use a mesh size that -9.5% below ($+3.3\%$ above) the first-best level. Although the fishermen with number quotas fish more selectively and hence more costly than socially optimal, their resulting revenue and cost increases relative to the first-best balance well, such that their profit is only -0.5% below the first-best level. The steady-state profits of fishermen with biomass quotas are -4.0% below the first-best profits.

With respect to the transition dynamics, the fishermen with biomass quotas face much stricter quotas in the rebuilding phase than the fishermen with number quotas. For example, the second-best biomass quota in the first year is -34.3% below the first-best catch in terms of biomass, whereas the second-best number quota is only -11.7% below the first-best catch in numbers. Because fishermen with biomass quotas prefer very low mesh sizes if large fish are absent in the stock (cf. Figure 3), the regulator reacts to these preferences by cutting down biomass quotas more sharply than number quotas in the rebuilding phase.

4 Conclusions

The deviations of the second-best profits relative to their first-best levels could be interpreted as the costs of deregulating the fishing gear choice. The question if these costs of deregulation outweigh the alternative costs of enforcing gear restrictions remains an empirical one and has to be decided on a case-by-case basis for each type of fishery. This also holds true for the question which second-best quota measure performs better in a specific fishery.

Nevertheless, the aim of this paper was to show that a change of "currency" in the way fishery quotas are measured may create substantial economic benefits simply by changing the incentives of fishermen. In most fisheries that face a growth overfishing problem, fish are usually sorted into size categories, or it would be feasible to do so at low costs. Estimating the number of fish landed should thus not be a problem of practical importance. If this is the case, switching to number quotas may be a simple way of increasing the economic performance of a fishery substantially. Yet, this presupposes that the quotas are set at their respective second-best levels, while in reality quotas are still often set at inefficiently high levels. Our analysis suggests that fishery management should shift the focus from designing a plethorea of different management instruments, including lots of gear restrictions, to setting the quotas right.

A Simple two age-class model: First-best

The complete first-order conditions for (3) are

$$h_{1t}\frac{\partial L}{\partial h_{1t}} = 0 \qquad \text{and} \qquad \frac{\partial L}{\partial h_{1t}} = p_1\, w_1 - \mu_t\, \alpha_1 \leq 0 \tag{33}$$

$$h_{2t}\frac{\partial L}{\partial h_{2t}} = 0 \qquad \text{and} \qquad \frac{\partial L}{\partial h_{2t}} = p_2\, w_2 - \mu_t\, \alpha_2 \leq 0 \tag{34}$$

$$\frac{\partial L}{\partial x_{2t}} = \lambda_t\, \gamma_1\, \varphi'\left(\gamma_1\, x_{1t} + \gamma_2\, x_{2t}\right) + \mu_t\, \alpha_1 - \frac{1}{b}\, \lambda_{t-1} = 0 \tag{35}$$

$$\frac{\partial L}{\partial x_{2t}} = \lambda_t\, \gamma_2\, \varphi'\left(\gamma_1\, x_{1t} + \gamma_2\, x_{2t}\right) + \mu_t\, \alpha_2 - \frac{1}{b}\, \mu_{t-1} = 0 \tag{36}$$

B Model with imperfect selectivity and fishing costs: First-best

Using $\lambda_{n,t} \equiv \lambda_{n-1t}$ and $s_t(\sigma_t) = \sum_{i=1}^{n} \lambda_{it}\, \alpha_i\, q_i(\sigma_t)\, x_{it}$, the problem (28) can be reformulated as

$$\begin{aligned}\max_{(H_t^z)_{t=1}^{\infty},(\sigma_t)_{t=1}^{\infty}} L = \sum_{t=1}^{\infty} b^t \Bigg\{ g\Bigg(\Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\, \omega_z(\sigma_t)\, H_t^z\Bigg) \\ + \lambda_{0,t}\, \varphi(\mathbf{x}_t) + \sum_{i=1}^{n} \left(\alpha_i\, \lambda_{it}\, x_{it} - \lambda_{i-1}\, x_{i,t+1}\right) - s_t(\sigma_t)\, \omega_z(\sigma_t)\, H_t^z\end{aligned} \tag{37}$$

A necessary condition for the first-best mesh size in period t follows as

$$\begin{aligned}\frac{\partial L}{\partial \sigma_t} =& g'\left(\cdot\right) \Bigg(\Big(r_t'(\sigma_t) - c_t'(\sigma_t)\Big)\omega_z(\sigma_t) + \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\omega_z'(\sigma_t)\Bigg)\, H_t^z \\ &- \Bigg(s_t'(\sigma_t)\, \omega_z(\sigma_t) + s_t(\sigma_t)\, \omega_z'(\sigma_t)\Bigg)\, H_t^z \overset{!}{=} 0\end{aligned} \tag{38}$$

C Model with imperfect selectivity and fishing costs: Static fishermen optimization problem

First-order conditions of the fisherman's static optimization problem (30) with $\bar{\lambda}_t$ for the quota constraint:

$$\frac{\partial \Pi_t}{\partial \sigma_t} = \left(\Big(r_t'(\sigma_t) - c_t'(\sigma_t)\Big)\omega_z(\sigma_t) + \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\omega_z^{'}(\sigma_t)\right) H_t^z \leq 0 \tag{39}$$

$$\frac{\partial \Pi_t}{\partial H_t^z} = \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\,\omega_z(\sigma_t) - \bar{\lambda}_t \leq 0 \tag{40}$$

$$\frac{\partial \Pi_t}{\partial \bar{\lambda}_t} = Q_t^z - H_t^z \geq 0 \tag{41}$$

$$\frac{\partial \Pi_t}{\partial \sigma_t}\,\sigma_t = 0, \quad \frac{\partial \Pi_t}{\partial H_t^z}\,H_t^z = 0, \quad \frac{\partial \Pi_t}{\partial \bar{\lambda}_t}\,\bar{\lambda}_t = 0, \quad \sigma_t, H_t^z, \bar{\lambda}_t \geq 0 \tag{42}$$

Selecting $\{H_t^z = 0,\, \sigma_t = 0\}$ from the numerous solutions in case of $\max_{\sigma_t \geq 0}\{R_t(\sigma_t) - C_t(\sigma_t)\} \leq 0$ to shorten notation, the optimal fisherman behaviour can be summarized as:

$$H_t^z = \begin{cases} 0, & \text{for} \quad \max_{\sigma_t \geq 0}\{r_t(\sigma_t) - c_t(\sigma_t)\} \leq 0 \\ Q_t^z & \text{for} \quad \max_{\sigma_t \geq 0}\{r_t(\sigma_t) - c_t(\sigma_t)\} > 0 \end{cases} \tag{43}$$

$$\sigma_t = \begin{cases} 0, & \text{for} \quad \max_{\sigma_t \geq 0}\{r_t(\sigma_t) - c_t(\sigma_t)\} \leq 0 \\ \tilde{\sigma}_t & \text{for} \quad \max_{\sigma_t \geq 0}\{r_t(\sigma_t) - c_t(\sigma_t)\} > 0 \end{cases} \tag{44}$$

with $\tilde{\sigma}_t$ defined by (31). As $\lim\limits_{\sigma_t \to 0} \Big(r_t'(\sigma_t) - c_t'(\sigma_t)\Big)\omega_z(\sigma_t) + \Big(r_t(\sigma_t) - c_t(\sigma_t)\Big)\omega_z^{'}(\sigma_t) = 0$, the case of $\{H_t^z = Q_t^z,\, \sigma_t = \tilde{\sigma}_t = 0\}$ is included in (31).

D Empirical model for the Eastern Baltic Cod trawl fishery

We use a profit-margin condition to estimate χ and c_0. This condition can be formulated as

$$\pi_t \equiv \left(\frac{\text{Profit}}{\text{Revenue}}\right)_t = \frac{r_t(\sigma_t) - c_t(\sigma_t)}{r(\sigma_t)}$$

Inserting $c(\sigma_t) = c_0\, B_t(\sigma_t)^{1-\chi}$, $r(\sigma_t) = \sum_{i=1}^n p_i\, w_i\, q_i(\sigma_t)\, x_{it}$ and $B_t(\sigma_t) = \sum_{i=1}^n w_i\, q_i(\sigma_t)\, x_{it}$ and taking logarithms after rearranging terms yields

$$\ln\left((1-\pi_t)\sum_{i=1}^n p_i\, w_i\, q_i(\sigma_t)\, x_{it}\right) = \ln\, c_0 + (1-\chi)\, \ln\left(\sum_{i=1}^n w_i\, q_i(\sigma_t)\, x_{it}\right) \tag{45}$$

For the retention probability $q_i(\sigma_t)$, we model a trawl net with a New Bacoma escape window in the codend (Feekings et al. 2013) as it is the most commonly used gear in the fishery. In a recent survey (EC 2013), 45 out of 66 interviewed fishermen used a codend with a New Bacoma escape window. Based on selectivity parameters taken from Madsen (2007), the retention probability $q_i(\sigma_t)$ can be formulated as

$$q_i(\sigma_t) = 1/\left(1 + e^{14.95 - 39.45\,\frac{l_i}{\sigma_t}}\right), \tag{46}$$

where l_i describes the mean length-at-age of age class i. Both length-at-age l_i and weight-at-age w_i data are taken from the Baltic International Trawl Survey, accessed through the supplementary material of Froese and Sampang (2013). Stock numbers in age class i and year t are taken from ICES (2014). Age-dependent prices for cod have been computed from price reports published by the German Federal Office of Agriculture and Food (BLE 2016).

Values for p_i, w_i, $q_i(\sigma_t)$, l_i, x_{it} have been available for the period 2003-2012. Exploiting the fact that quotas were non-binding in 2003 and since 2008, the open-access zero profit condition $\pi_t = 0$ must hold for $2003, 2007 - 2012$. As values of B_t in the period 2004-2007 are similar to those in the period with non-binding quotas, we assume $\pi_t = 0$ for the years 2003-2007 as well. The mesh sizes σ_t are taken from the official regulations (Feekings et al. 2013, EC 2010).

Using simple OLS with $n = 10$, estimating (45) yields $\ln c_0 = 2.038\,(0.509)$ and $1 - \chi = 0.621\,(0.125)$, standard error in parentheses. These estimates were used to calculate $c_0 = 0.379$ and $\chi = 7.676$. A Ricker (1954) stock-recruitment function is used to model recruitment as

$$x_{1,t+1} = \varphi(\mathbf{x}_t) = \phi_0 \left(\sum_{i=1}^{n} w_i\,\gamma_i\,x_{it}\right) e^{-\left(\sum_{i=1}^{n} w_i\,\gamma_i\,x_{it}\right)/\phi_1}, \tag{47}$$

where the maturity-at-age values γ_i are taken from ICES (2014) and $\chi_0 = 1.699$, $\chi_1 = 549.451$ are taken from Quaas et al. (2016). The instantaneous natural mortality rate is set to 0.2 for all age classes, which corresponds to an annual natural survival rate of $\alpha_i = 0.82$. All age-dependent parameter values are summarized in Table 1. To prevent pulse fishing, we use $g(\cdot) = (\cdot)^{0.8}$ in our model.

The starting year of our computations is 2013, the discount factor was set to $b = 0.95$, corresponding to a discount rate of about 5%. The AMPL software package (Fourer et al. 2009) was used to solve the optimization problems (28) and (32) with $T = 100$ numerically.

age class	1	2	3	4	5	6	7	8
p_i	0	0	1.22	1.22	1.75	1.75	2.27	2.27
w_i	0	0.16	0.45	0.81	1.20	1.80	2.65	3.65
l_i	0	25.09	34.95	42.76	49.24	56.59	63.70	70.10
α_i	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
γ_i	0	0.13	0.36	0.83	0.94	0.96	0.96	0.98
$x_{i,0}$	194.853	173.859	105.768	63.768	28.198	14.333	5.447	2.298

Table 1: Age-dependent parameter values of the Eastern Baltic Cod fishery example.

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