Should Fishing Quotas Be Measured in Terms of Numbers?

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ABSTRACT

Whereas rights-based catch regulations such as individual transferable quotas (ITQs) are gaining traction as the key management instrument in many fisheries, most fisheries are additionally regulated by gear restrictions, minimum landing sizes, and similar measures that intend to protect young fish from being caught. Here we study the incentives to fish selectively in a second-best setting, where the regulator issues quotas of different types and fishers choose the size of the fish they catch. We find that if quotas are specified in terms of the number of fish, rather than biomass or weight, fishers have substantial incentives to target larger fish. Thus juvenile fish are protected without need for gear restrictions. We develop the economic principles in an analytical model and quantify results for empirical examples. We find that steady-state profits under second-best deregulated number quota management are only 0.1%–2.1% below the first-best optimum.

INTRODUCTION

Fisheries are the prime textbook example of common property resources, and it is well established that regulation is required to prevent overuse of such resources (Stavins 2011). Accordingly, most real-world fisheries are tightly regulated. Regulations include licensing and restrictions of fishing seasons and areas, as well as on the types, sizes, and technical features of gear that may be used, and many measures more (UN 1982, Articles 61–62). A particularly important regulation is to limit the total allowable catch (TAC), and this regulation is actually required by the United Nations Law of the Sea Convention UN 1982, Article 61, 1) for fisheries within the exclusive economic zones.

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In most developed countries, rights-based catch regulations, such as individual tradable quotas (ITQs), have gained traction as central management instruments for fisheries and have contributed to greatly improve the efficiency of fisheries (Grafton et al. 2005; Costello, Gaines, and Lynham 2008; Costello et al. 2016; Isaksen and Richter 2019). To achieve dynamic efficiency, such catch regulations have to adequately take into account the fish population dynamics. Marine biologists emphasize that this includes in particular the age structure of the fish population (Walters and Martell 2004). However, almost all existing quota systems for commercial fisheries specify quotas in terms of the weight (biomass) of landings of a particular species of fish, with no explicit consideration of the age or size structure of the catch. The question arises whether this is the best approach, especially as the previous literature on age-structured fisheries has proposed the alternative approach of measuring quotas in terms of the number of individual fish (Diekert 2013; Quaas et al. 2013). In this paper, we compare the economic implications of these two alternative ways to measure quotas.

We develop a theoretical bioeconomic model of a fishery on a size-structured population that compares the first-best (the manager determines overall catch and size structure in catch) with the situation where the manager solely constrains the overall catch (by issuing quotas either in terms of numbers or in terms of biomass), while the fishers are free to choose the size structure in catch as they like.

In theory, the first-best could be implemented by means of fully delineated individual quotas (Costello and Deacon 2007), here according to size classes (Diekert 2012; Quaas et al. 2013). If quotas are specified in terms of numbers or biomass, but not fully delineated, in general only a second-best outcome can be obtained. Contrary to the previous literature (Diekert 2012; Quaas et al. 2013) that considered more special cases, we find that in general the two types of second-best quota regulation, that is, in terms of numbers or biomass, cannot be ranked in terms of welfare implications. We find that number quotas set stronger incentives for fishers to target large fish than do biomass quotas, but to such an extent that the incentives to target large fish tend to be even stronger than socially optimal. It is thus an empirical question which quota measure is superior for real-world fisheries. Consequently, we calibrate the second-best model for three large fisheries and quantify the welfare effect of either management approach for Northeast Arctic cod, Eastern Baltic cod, and Northeast Atlantic mackerel.

Our paper introduces findings and methods from the literature on second-best regulation of differentiated environmental externalities to fisheries economics. Kolstad (1987) studies the case where emissions from different sources contribute differently to marginal environmental damage. A first-best policy would thus regulate emission sources differently (Montgomery 1972), and Kolstad (1987) shows that the welfare loss from a uniform regulation is larger the steeper the marginal damage and marginal abatement cost functions are. The welfare loss of a uniform regulation of sources of heterogeneous pollution have been quantified, for example, for biodiversity conservation (Wätzold and Drechsler 2005) and groundwater pumping (Kuwayama and Brozović 2013). None of these papers compares alternative approaches of uniform regulation. If the environmental damage depends not only on emissions, but also on environmental conditions, a first-best regulation for one source requires differentiation according to the current environmental conditions. For such a problem, Hamilton and Requate (2012) study whether emission or ambient standards are preferable to regulate stochastic pollution, when the regulator cannot adjust standards to the realization of stochastic (weather) shocks. They find that an emission standard is superior to an ambient standard if the marginal damage function is relatively steep. These approaches have in common that they consider the welfare-maximizing choice of regulation from a restricted set of instruments, anticipating how the regulated subjects will respond by making decisions in their self-interest. For the present problem, this translates into a dynamic Stackelberg game between a regulator and competitive fishers, which we numerically solve as a bi-level dynamic optimization problem.

We build on, and extend, the literature that analyzes harvesting of resource stocks that have an internal structure (Tahvonen 2009; Smith, Sanchirico, and Wilen 2009). While our model abstracts from spatial considerations (Smith, Sanchirico, and Wilen 2009; Bode, Sanchirico, and Armsworth 2016; Sampson 2018) or species interactions (Finnoff and Tschirhart 2003; Quaas and Requate 2013), it explicitly accounts for the age structure of the fish populations, endogenizing not only total catches, but also the choice of fishing gear in empirically quantified models in a dynamic equilibrium. Most of the existing studies on harvesting age-structured fish populations focus on optimal management (e.g., Diekert et al. 2010; Tahvonen et al. 2013; Tahvonen, Quaas, and Voss 2018; Quaas and Tahvonen 2019). This literature provides substantial evidence that the optimal harvesting targets large fish, and that it would not be optimal to spare the very old and large fish, even if gear selectivity allows (Tahvonen, Quaas, and Voss 2018). Here we consider the decentralized setting and study how to design individual quotas in order to deregulate gear choice while minimizing unwanted consequences for the size structure of fish populations. We find that the welfare costs of dropping gear regulations and allowing fishers to freely determine their target fish size would come at small welfare costs, provided that the quotas are set (second-best) optimally. For the cod fisheries studied, this would mean that fishing quotas would need to be set in numbers. Overall our analysis thus opens new perspectives to rethink fisheries regulation.

THEORY: SIMPLIFIED SIZE-STRUCTURED MODEL

We start with a theoretical analysis that assumes perfect selectivity and abstract from fishing cost to study the fundamental trade-offs involved in choosing the size structure of the harvest. Gear selectivity based on field studies is taken into account in the subsequent quantitative analysis.

Let x_{st} be the number of fish in size class $s = 0, 1, \ldots$ at time $t = 0, 1, \ldots$, both unbounded from above. Following Tahvonen (2015), the dynamics of the size-structured fish stock is then given by the following:

$$x_{0,t+1} = \varphi + \beta x_{0t}, \tag{1a}$$

$$x_{s+1,t+1} = \alpha x_{st} + \beta x_{s+1,t} - h_{st}, \quad s = 0, 1, \ldots, \tag{1b}$$

with given initial population $x_{s0} \geq 0$, $s = 0, 1, \ldots$. Here, $\varphi > 0$ denotes recruitment, which we assume to be constant, an assumption not uncommon in the literature (Hannesson 1975; Tahvonen, Quaas, and Voss 2018), but to be replaced by a stock-recruitment model below. The fraction $\alpha > 0$ of fish growing into the next size class and the fraction $\beta > 0$ remaining in the same size class are independent of the size class. Overall, a fraction $\alpha + \beta < 1$ of fish from any size class survives natural mortality. Note that the age-structured model is obtained for the special case $\beta = 0$.

The number of harvested fish from size class s is denoted by h_{st}. As we ignore fishing cost for the time being, the objective is to maximize the present value, at discount factor $b = 1/(1 + r)$ with discount rate $r > 0$, of revenues from fishing,

$$\max_{\{h_{st}\in[0,\alpha x_{st}+\beta x_{s+1,t}]\}} \sum_{t=0}^{\infty}\sum_{s=0}^{\infty} b^t p_s w_s h_{st}, \tag{2}$$

where p_s is the price, and w_s is the weight, of fish in size class s. Fish continue to grow during their lifetime, that is, $w_{s+1} > w_s$ for all $s = 0, 1, \dots$, and also the value of an individual fish is increasing with size, $p_{s+1}w_{s+1} > p_s w_s$. This condition is always fulfilled if the price increases with size (as is empirically the case for many fisheries; Zimmermann and Heino 2013), or if the price decrease is compensated by the weight increase. We discuss below how the results change if this condition is not fulfilled.

The first-best solution is obtained by maximizing equation 2 subject to population dynamics. We first study this problem and then turn to the second-best problems where the planner chooses the (second-best) optimal time path of either a biomass quota $Q^B = \Sigma_{s=0}^{\infty} w_s h_{st}$ or a number quota $Q^N = \Sigma_{s=0}^{\infty} h_{st}$, whereas fishers are free to choose the profit-maximizing size composition of catch given the respective quota constraint.

FIRST-BEST HARVESTING

To characterize first-best, we determine size-specific harvest quantities h_{st} to maximize equation 2, subject to biological population dynamics (equation 1) and nonnegativity of h_{st} and x_{st}. We use λ_{0t} to denote the Lagrangian multiplier for the recruitment constraint (equation 1a) in period t, $\lambda_{s+1,t}$ to denote the Lagrangian multiplier for the survival and growth constraint (equation 1b), μ_t to denote the Kuhn-Tucker multiplier for the constraint $h_{st} \geq 0$, and ν_t for the constraint $h_{st} \leq \alpha x_{st} + \beta x_{s+1,t}$. The first-order conditions for optimal harvesting are, for $s = 0, 1, \dots$,

$$p_s w_s - \lambda_{s+1,t} + \mu_{st} - \nu_{st} = 0, \tag{3a}$$

$$b\alpha\lambda_{s+2,t+1} + b\beta\lambda_{s+1,t+1} - \lambda_{s+1,t} + b\alpha\nu_{s+1,t+1} + b\beta\nu_{s,t+1} = 0, \tag{3b}$$

with complementary slackness conditions $\mu_{st}h_{st} = 0$ and $\nu_{st}(\alpha x_{st} + \beta x_{s+1,t} - h_{st}) = 0$. We focus on a steady state, where $\lambda_s \equiv \lambda_{st} = \lambda_{s,t+1}$, $\mu_s \equiv \mu_{st} = \mu_{s,t+1}$, and $\nu_s \equiv \nu_{st} = \nu_{s,t+1}$ are constant. As shown by Reed (1980), the optimal harvest in steady state involves harvesting from at most two size classes. Given the monotonicity assumption on $p_s w_s$, these must be subsequent size classes.

Denote by s^* a size class with positive harvesting, that is, where $p_{s^*}w_{s^*} = \lambda_{s^*+1}$. Using this in equation 3b, and combining with equation 3a for size class $s^* + 1$, we obtain that s^* is determined by the condition $p_{s^*+1}w_{s^*+1} \leq (1 - b\beta) / (b\alpha)p_{s^*}w_{s^*}$, or equivalently,

$$\frac{p_{s^*+1}w_{s^*+1} - p_{s^*}w_{s^*}}{p_{s^*}w_{s^*}} \leq \rho \equiv \frac{1 - b(\alpha + \beta)}{b\alpha}. \tag{4}$$

This condition is intuitive: one should harvest all fish of the size class from which onwards the growth rate of the value of an individual fish, given by the left-hand side of condition 4, is smaller than a discount rate $\rho > 0$ that compounds economic and biological discounting.[1] If there was no natural mortality and if all fish would grow into the next size class, in other words in case $\alpha = 1$ and $\beta = 0$, the term on the right-hand side of equation 4 is simply the economic discount rate $\rho = r = 1/b - 1$. If some fish die from natural mortality, $\alpha < 1$, or not all fish grow into the next size class, $\beta > 0$, the compound discount rate includes the effects of "biological

1. The compound discount rate is positive, as $b = 1/(1 + r) < 1$ and $\alpha + \beta < 1$.

discounting" (Skonhoft, Vestergaard, and Quaas 2012), and thus is reduced to the value given on the right-hand side of condition 4.

For all size classes smaller than s^*, we obtain for the Lagrangian multiplier, that is, the shadow price of fish of size class s,

$$\lambda_s = (1+\rho)^{s-s^*} p_{s^*} w_{s^*}, \tag{5}$$

which is monotonically increasing, as the compound discount rate is positive, $\rho > 0$.

Figure 1 illustrates the optimal size-specific harvesting in steady state, assuming that λ_{s+1} grows linearly with s. The fish shadow price $p_s w_s$ is everywhere larger than the fish market value s^*, except for the size class s^* where it is equal to $p_{s^*} w_{s^*}$. The numbers of fish x_s decrease with size class s because of natural mortality. Because of the linear objective function, it is optimal to harvest all fish at the optimal size class s^*.

SECOND-BEST QUOTA MANAGEMENT

The problem for the regulator thus is to choose the time path of total catches—in terms of the biomass or number of fish—to maximize equation 2, given that fishers choose the profit-maximizing size composition of the catch under the respective quota constraint.

This can be seen as a dynamic game between the regulator (Stackelberg leader) and the fishers (Stackelberg followers). To find the subgame-perfect equilibrium, the problem is solved

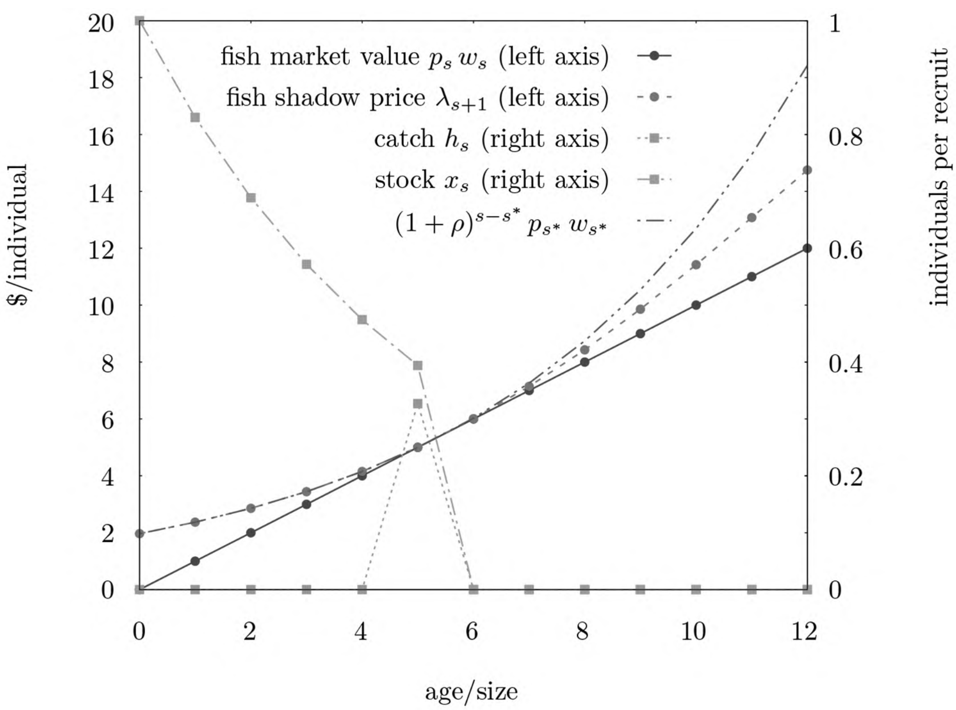

Figure 1. Illustration of Optimal Size-Specific Harvesting in Steady State, Assuming That $p_s w_s$ Grows Linearly with s. Left axis gives the price per individual, right axis gives the number of individual fish per recruit that are harvested or in the fish stock (implying a normalization to 1 at age 0). A color version of this figure is available online.

backwards, first looking at the optimal reaction of a representative fisher being regulated by a given quota Q. Throughout, we assume that each individual fisher's quota is small relative to the total allowable catch, which also implies that the fisher does not consider how his targeting of size classes affects future fish population dynamics. Thus, the only constraint that a fisher faces when choosing harvest quantities h_{st} to maximize current profit is the quota in the current period.

We consider first the case that the fisher is regulated by biomass quotas, such that in each period the quota constraint is $\Sigma_{s=0}^{\infty} w_s h_{st} \leq Q_t^B$. Using λ_t^B to denote the Lagrangian multiplier for this constraint, the fisher will choose harvest rates according to the condition $p_s w_s - w_s \lambda_t^B \leq 0$, with equality if $h_{st} > 0$ and strict inequality if $h_{st} = 0$. In steady state, $\lambda^B = \lambda_t^B$ is constant over time, and the fisher will target fish of sizes $s \geq s^B$, where

$$s^B = \min\{s | p_s \geq \lambda^B\}. \tag{6}$$

Similarly, a fisher facing individual number quotas Q_t^N will choose harvest such as to maximize current profits subject to the constraint $\Sigma_{s=0}^{\infty} h_{st} \leq Q_t^N$ in each period t. Using λ_t^N to denote the Lagrangian multiplier for this constraint, the condition determining optimal harvest is $p_s w_s - \lambda_t^N \leq 0$. In steady state, the fisher will target fish of sizes $s \geq s^N$, where

$$s^N = \min\{s | p_s w_s \geq \lambda^N\}. \tag{7}$$

COMPARING FIRST-BEST AND SECOND-BEST UNDER BIOMASS AND NUMBER QUOTAS

Juxtaposing the conditions for targeting sizes in first-best steady state, $p_s w_s \geq \lambda_{s+1}$ from equation 3a, and in second-best under biomass quotas (equation 6) and number quotas (equation 7), illustrates the different factors that affect which size class is targeted. It may be illustrative to view the problem of the agent (the fishery manager, or the fisher) as the question of when to exercise the harvesting option. As discussed above, the fishery manager considers mortality, time discounting, the increase in weight, and the increase in price. A fisher who holds a number quota considers the increase in weight and the increase in price. He exercises his option when the opportunity cost of holding on to the current quota exceeds the cost of acquiring a new one (equation 7). Under biomass quotas, only the increase in prices affects the choice (equation 6). In particular, this implies that the option is exercised immediately (fishing will be completely nonselective) if prices do not increase with size.

As weights strictly increase with size, this suggests that number quotas will lead to targeting a larger size class than will biomass quotas. Moreover, as fishers regulated by number quotas ignore economic and biological discounting, number quotas will lead to targeting larger size classes than optimal. To be able to compare the three settings more formally, consider a situation in which the two second-best regimes are regulated such that the incentives to harvest a recruit of age 0 are the same, and that the opportunity costs of harvesting an individual recruit in both settings are equal to the steady-state shadow price of a recruit, that is, assume $\lambda^N = w_0 \lambda^B = \lambda_0$. For this situation, we have the following proposition.

Proposition 1. (Targeted size class) Consider a steady state and assume $\lambda^{\mathrm{N}} = \mathrm{w}_0 \lambda^{\mathrm{B}} = \lambda_0$. Then:

(a) A larger size class will be targeted under number quota management than under biomass quota management.
(b) A larger size class will be targeted under number quota management than under first-best harvesting.
(c) A larger size class will be targeted under biomass quota management than under first-best harvesting if and only if the increase in weight exceeds the discounting due to mortality and time preference, $w_{s^*} / w_0 \geq (1 + \rho)^{s^*}$.

Proof. From equation 5 we conclude $\lambda_0 = (1 + \rho)^{-s^*} \lambda_{s^*}$. The size class s^* targeted under optimal fishing is determined by

$$(1 + \rho)^{-s^*} p_{s^*} w_{s^*} = \lambda_0. \tag{8}$$

Using $\lambda^N = w_0 \lambda^B = \lambda_0$ in conditions 6 and 7, we find that the size class targeted under biomass quotas is the smallest s^B satisfying $p_{s^B} \geq \lambda^B = \lambda_0 / w_0$, or equivalently $p_{s^B} w_0 \geq \lambda_0$, and that the size class targeted under number quotas is the smallest s^N satisfying $p_{s^N} w_{s^N} \geq \lambda^N = \lambda_0$. Part (a) of the proposition follows from the comparison of the two conditions determining s^B and s^N and the fact that $w_{s^N} \geq w_0$. Part (b) follows from the comparison of the two conditions determining s^* and s^N and the fact that $(1 + \rho)^{-s^*} \leq 1$. Part (c) follows from the comparison of the two conditions determining s^* and s^B. □

Management by number quotas thus induces targeting of larger size classes compared with both first-best and management by biomass quotas. In contrast, the selectivity ranking between biomass quotas and first-best is generally ambiguous. In the specific case that the price does not increase with fish size, however, biomass quotas unambiguously imply targeting too small fish.

The stronger the increase in weight, relative to the increase in the price, the larger the wedge between number quota and biomass quota management. Similarly, the smaller the natural mortality rate and the smaller the compound discount rate ρ, the smaller is the wedge between number quotas and first-best management. That is, we would expect number quotas to come close to first-best in fisheries where growth overfishing is an important issue (strong increase in weight and low mortality). Conversely, when growth in weight is relatively small, but the increase in price induces incentives to target large fish, biomass quotas perform relatively well.

Recruitment is constant in our simple model. The decision which size class to select depends on the comparison of the growth rate with the (compound) discount rate, which is independent of the population size. Endogeneous recruitment would be reflected by a term that captures the marginal future value of the offspring (fecundity). This will typically favor number quotas over biomass quotas, as fecundity is generally increasing with size. We include this effect in the more detailed model developed in the next section.

We did not derive the second-best optimal quota management for the theoretical model here. Indeed, if we only focus on a steady state, the assumptions of a linear objective without harvesting costs and perfect selectivity lead to a corner solution with harvesting from one or two size classes only. As a consequence, it is always possible to specify number quotas that, in steady state, implement the first-best optimal size selectivity and thus also harvest quantity. If the prices are monotonically increasing with size, the same is true for biomass quotas. One reason for this result is that ignoring fishing costs also means to ignore the costs of fishing selectively, which may be an important motivation for fishers to catch smaller fish. In the next section we specify a more detailed model with harvesting costs and imperfect selectivity of fishing methods that we then empirically quantify for real-world fisheries.

DETAILED EMPIRICAL MODEL WITH IMPERFECT SELECTIVITY AND FISHING COSTS

GENERAL STRUCTURE

The more detailed model of a fishery on a size-structured population developed in the following serves two purposes. First, it introduces the model structure that we take to the data of our three real-world examples, the Northeast Arctic cod fishery (NEAC), the Eastern Baltic cod fishery (EBC), and the Northeast Atlantic mackerel fishery (NEAM). Second, it allows us to show that our main results from the simple model carry over to a more realistic, complex model.

Imperfect selectivity. The first modification of our simple model is that we allow for imperfect size selectivity (Madsen 2007; Quaas et al. 2013; Tahvonen, Quaas, and Voss 2018). In our model this means that the fisher can only adjust fishing effort E_t and a selectivity parameter σ_t of fishing gear, such as mesh size of a trawl gear, but can not independently choose harvest quantities for each age class.

Let $q_s(\sigma_t) \in [0, 1]$ denote the retention probability of a fish of size class $s = 1, \dots, n$ entering a gear whose selectivity parameter is $\sigma_t \in [\underline{\sigma}, \leq \bar{\sigma}]$, where the lower ($\underline{\sigma} \geq 0$) and upper ($\bar{\sigma} > \underline{\sigma}$) bounds depend on the specific fishing technology.

The retention probability is decreasing with $q_s'(\cdot) < 0$. Figure 2 shows the retention probability curve for the trawl net considered in one of our empirical examples (the Eastern Baltic cod fishery, discussed in the empirical examples section below). This figure shows, for example, that with a mesh size of 150 mm a fish of size corresponding to an age of five years is caught with about 10% probability, while with a mesh size of 120 mm, a fish of the same size class is caught with about 80% probability.

The imperfectly selective fishing gear naturally leads to the definition of the *harvestable biomass* as the sum of fish from the different size classes times their size-specific weight times their size-specific retention probability:

$$B_t(\sigma_t, \mathbf{x}_t) = \sum_{s=1}^{n} q_s(\sigma_t) w_s x_{st}. \tag{9}$$

The harvestable biomass (the harvestable number of fish) can be interpreted as the biomass caught in period t (the total number of fish caught) that would result if all fish $\mathbf{x}_t = (x_{1t}, x_{2t}, \dots)$ in period t entered a fishing net with mesh size σ_t once.[2]

Similarly, we will define *harvestable number of fish* as $N_t(\sigma_t, \mathbf{x}_t) = \sum_{s=1}^{n} q_s(\sigma_t) x_{st}$ and the *harvestable shadow value* of the fish stock as $S_t(\sigma_t, \mathbf{x}_t) = \sum_{s=1}^{n} \lambda_{st} \alpha_s q_s(\sigma_t) x_{st}$, where λ_{st} is the shadow price of the stock of fish in size class s at time t, derived from a planner's optimization problem. The harvestable shadow value can be interpreted as the opportunity costs of all fish $\mathbf{x}_t$ having contact with a fishing net with mesh size σ_t once. Per size class, $q_s(\sigma_t)x_{st}$ fish would get entangled in the net, and their harvest is valued by the social planner with the shadow price λ_{st}. As an unharvested fish is exposed to natural mortality, the shadow price is only calculated based on the

2. Note that while Tahvonen, Quaas, and Voss (2018) use the term *efficient biomass* for the same concept, here we adopt the terminology of Zimmermann and Jørgensen (2015).

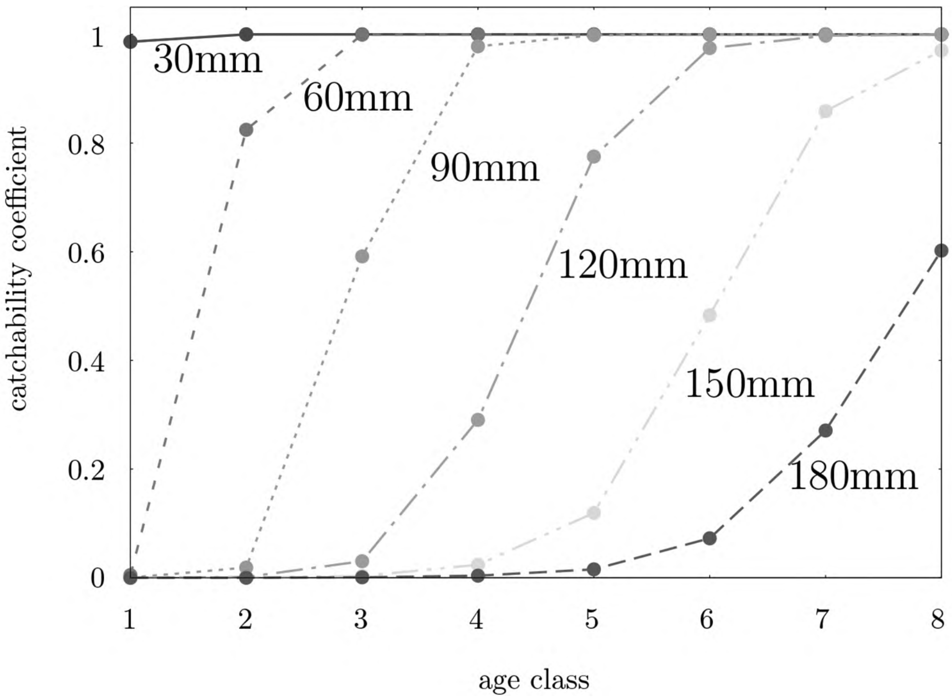

Figure 2. Retention Probabilities of Eastern Baltic Cod as a Function of Size for Different Mesh Sizes σ_t. The smaller the mesh size, the higher the probability that a fish of a given size class is caught. A color version of this figure is available online.

fraction α_s that would survive natural mortality from period t to $t + 1$. Online appendix A presents a detailed derivation of the conditions that characterize first-best harvesting, that is, time paths of size-specific catches that maximize the present value of economic surplus from the fishery, as described below.

From now on, we will drop all time subscripts and suppress the argument $\mathbf{x}$ when expressing the harvestable biomass B, the harvestable number of fish N, or the harvestable shadow value S. While our model is fully dynamic, and different selectivity and stock values will play a role during the transition to the steady state in the empirical examples, simplifying the notation removes clutter and emphasizes the key parameter of interest: the first- and second-best choice of selectivity.

We assume that the share of size class s in total number of fish that are harvested, H^N, equals its share in the harvestable number of fish:[3]

$$\frac{h_s}{H^N} = \frac{q_s(\sigma)x_s}{N(\sigma)}. \tag{10}$$

The idea of this assumption is that varying the mesh size σ captures the full potential to affect selectivity, whereas the size distribution is the same across all fish accumulations within the geographic range of the stock. In other words, we disregard the effect of fishing location choice on

3. Note that this implies that the share of size class s in total biomass that is harvested, H^B, equals its share in harvestable biomass: $\frac{w_s h_s}{H^B} = \frac{q_s(\sigma)w_s x_s}{B(\sigma)}$.

the size composition in catch. Similarly, differences in fish behavior (e.g., caused by different swimming speed or learned gear avoidance) do not matter. This underestimates the capabilities of fishers to influence fishing selectivity (Branch and Hilborn 2008; Abbott, Haynie, and Reimer 2015) and hence the potential differences between number and biomass quotas. Modeling fishing selectivity as being influenced by factors such as towing speed, gear depth, and location choice would require a much more detailed, spatially explicit model that also resolves within-season fish dynamics. This is beyond the scope of this paper, where we focus on fishing gear choice as it is the margin that is predominantly regulated in actual fisheries management.

Using equation 10, the number of fish caught from size class s can be described as the following:

$$h_s = q_s(\sigma)x_s \frac{H^N}{N(\sigma)} = q_s(\sigma)x_s \frac{H^B}{B(\sigma)}. \tag{11}$$

Using equation 10 we can also calculate mean weight in catch as $\frac{H^B}{H^N} = \frac{B(\sigma)}{N(\sigma)}$. We assume that increasing the mesh size increases the mean weight in catch, which reflects the idea that increasing the mesh size increases the selection of large fish relative to small ones:[4]

$$\frac{\partial}{\partial\sigma}\left(\frac{B(\sigma)}{N(\sigma)}\right) > 0 \qquad \forall\ \sigma \in [\underline{\sigma}, \bar{\sigma}]. \tag{12}$$

Fishing cost. To complete the description of a more realistic profit function, we now turn to discuss the cost structure. We adopt the generalized Schaefer harvesting function known from biomass models with constant $0 < \chi \leq 1$ to model potential hyperstability (Harley, Myers, and Dunn 2001) in catch rates during stock declines:

$$H_t^B = B_t(\sigma_t, \mathbf{x}_t)^{\chi} E_t. \tag{13}$$

With constant marginal costs $c_0 > 0$ of fishing effort E_t, the cost function in terms of the mesh size σ_t, number of fish in the stock $\mathbf{x}_t$, and total catch in biomass H_t^B is

$$C\left(\sigma_t, \mathbf{x}_t, H_t^B\right) = c_0 B_t(\sigma_t, \mathbf{x}_t)^{-\chi} H_t^B. \tag{14}$$

Using $p_s \geq 0$ to denote the size-specific fish prices per unit of biomass, fishing profits in biomass terms follow as

$$\Pi\left(\sigma, \mathbf{x}, H^B\right) = \left(\sum_{s=1} p_s w_s q_s(\sigma) x_s - c_0 B(\sigma)^{1-\chi}\right) \frac{H^B}{B(\sigma)}, \tag{15}$$

and in number as

$$\Pi\left(\sigma, \mathbf{x}, H^N\right) = \left(\sum_{s=1} p_s w_s q_s(\sigma) x_s - c_0 B(\sigma)^{1-\chi}\right) \frac{H^N}{N(\sigma)}. \tag{16}$$

To shorten notation, we define

4. It is a theoretical possibility that at huge mesh sizes selectivity decreases again, as then retention probabilities for all size classes tend to zero. For the empirical cases studied in this paper, assumption 12 is fulfilled for all relevant specifications of the model.

$$\pi(\sigma) \equiv \sum_{s=1} p_s w_s q_s(\sigma) x_s - c_0 B(\sigma)^{1-\chi}. \tag{17}$$

The profit would be $\pi(\sigma)$ if the actual number of harvested fish was equal to the harvestable number of fish, or equivalently if the actual biomass harvested was equal to the harvestable biomass. We thus call $\pi(\sigma)$ the *harvestable profit*. This completes the description of the profit function. It should be noted that we do not explicitly model the cost of changing the selectivity of the gear σ because gears have to be routinely replaced, irrespective of the chosen mesh size, and the costs of doing so do not depend on the chosen selectivity for a given gear.[5] Similarly, we do not explicitly model capital cost or other investments.

The social objective is to maximize the present value of net economic surplus, equal to fishing profits in the present setting:

$$\max \sum_{t=0}^{\infty} b^t \pi(\sigma) \frac{H^N}{N(\sigma)} = \max \sum_{t=0}^{\infty} b^t \pi(\sigma) \frac{H^B}{B(\sigma)}. \tag{18}$$

In the first-best setting, the planner optimizes over both harvest quantities and mesh sizes, whereas in the second-best setting the planner optimizes over the time path of quotas, whereas the fishers choose the mesh sizes that maximize current profit for the given quota. As usual, we start the analysis of second-best management by studying the fisher's reaction to the quota before we turn to the first stage of quota setting.

Second stage in second-best management: Fishers optimizing mesh sizes. A fisher regulated by a biomass quota Q^B chooses catch and mesh size to maximize current profit:

$$\max_{\sigma \in [\underline{\sigma}, \bar{\sigma}], H^B \in [0, Q^B]} \pi(\sigma) \frac{H^B}{B(\sigma)}. \tag{19}$$

As the objective function is linear in H^B, the fisher will harvest the entire quota if fishing is profitable, and otherwise the fisher will harvest nothing at all. More interesting is the optimal choice of mesh size:

$$\sigma^B = \arg \max_{\sigma \in [\underline{\sigma}, \bar{\sigma}]} \frac{\pi(\sigma)}{B(\sigma)}. \tag{20a}$$

Likewise, the optimal mesh size for fishers regulated by number quotas is

$$\sigma^N = \arg \max_{\sigma \in [\underline{\sigma}, \bar{\sigma}]} \frac{\pi(\sigma)}{N(\sigma)}. \tag{20b}$$

The mesh size decision of the social planner can be interpreted as maximizing the profit per unit of shadow value removed from the stock (cf. online appendix A, equation A-4),

$$\sigma^S = \arg \max_{\sigma \in [\underline{\sigma}, \bar{\sigma}]} \frac{\pi(\sigma)}{S(\sigma)}. \tag{20c}$$

5. The replacement intervals depend on the actual gear part in question, ranging from several times a year for gill nets or the ropes of a trawl net, to three- to five-year intervals for purse seines.

Note that the mesh size decision is independent of the amount of quota, as profit is linear in catch. Taking into account the relative abundance and profit contribution of each size class at sea, the mesh size decision optimizes the value per unit of catch, which is the harvestable profit per unit of harvestable resource base. While the harvestable resource base for a fisher regulated by a biomass quota is the harvestable biomass, it is the harvestable number of fish for a fisher regulated by a number quota. From the social planner's perspective, the correct measure of the harvestable resource base is the harvestable shadow value.

For the case that fishing is profitable, the solutions for equations 20a–20c are determined by the following necessary conditions under the three decision problems:

$$\pi'\left(\sigma^B\right) = \frac{\pi(\sigma^B)}{B(\sigma^B)} B'\left(\sigma^B\right) \qquad \text{for biomass quotas,} \tag{21a}$$

$$\pi'\left(\sigma^N\right) = \frac{\pi(\sigma^N)}{N\left(\sigma^N\right)} N'\left(\sigma^N\right) \qquad \text{for number quotas,} \tag{21b}$$

$$\pi'\left(\sigma^S\right) = S'\left(\sigma^S\right) \qquad \text{in first-best.} \tag{21c}$$

In all three institutional settings, the optimal mesh size is characterized by the condition that the marginal harvestable profit, that is, the marginal profit when fully harvesting the respective resource base, is equal to the value of changing the resource base by adjusting mesh size. For the two settings of quota management, the change of harvestable resource base is valued at the respective quota price, that is, the profit per unit of quota. For the social planner, the harvestable resource base is measured directly in value terms, thus the right-hand side of equation 21c contains only the marginal change of the resource base.

As in our simple model above, biomass quotas do have an important weakness if fishing selectively is socially optimal but costly:

Proposition 2. If prices do not depend on size class, $p_s = \bar{p}$ for $s = 1, \dots, n$, the profit per unit of biomass is strictly decreasing with mesh size,

$$\frac{\partial}{\partial \sigma}\left(\frac{\pi(\sigma)}{B(\sigma)}\right) < 0, \tag{22}$$

such that nonselective fishing becomes optimal for the fisher that is regulated by a biomass quota (i.e., $\sigma^B = \underline{\sigma}$).

Proof. Using $p_s = \bar{p}$ in equation 15, we have $\frac{\partial}{\partial \sigma}(\frac{\pi(\sigma)}{B(\sigma)}) = \frac{\partial}{\partial \sigma_t}(\bar{p} - c_0 B(\sigma)^{-\chi}) = \chi c_0 B_t(\sigma)^{-\chi-1} B'(\sigma) < 0$ as harvestable biomass decreases with σ. □

Regulating fishers with biomass quotas if the fish price is independent of size will hence unambiguously result in growth overfishing. Note that uniform prices are a sufficient but not a necessary condition for this effect to arise. In our example of the Northeast Arctic cod fishery, prices increase with size, but still fishers may choose nonselective fishing gear when faced with a biomass quota (see figure 3).

By contrast, number quotas always result in a (weakly) larger mesh size chosen by the fishers compared with biomass quotas, if the optimization problem of fishers with number quotas is

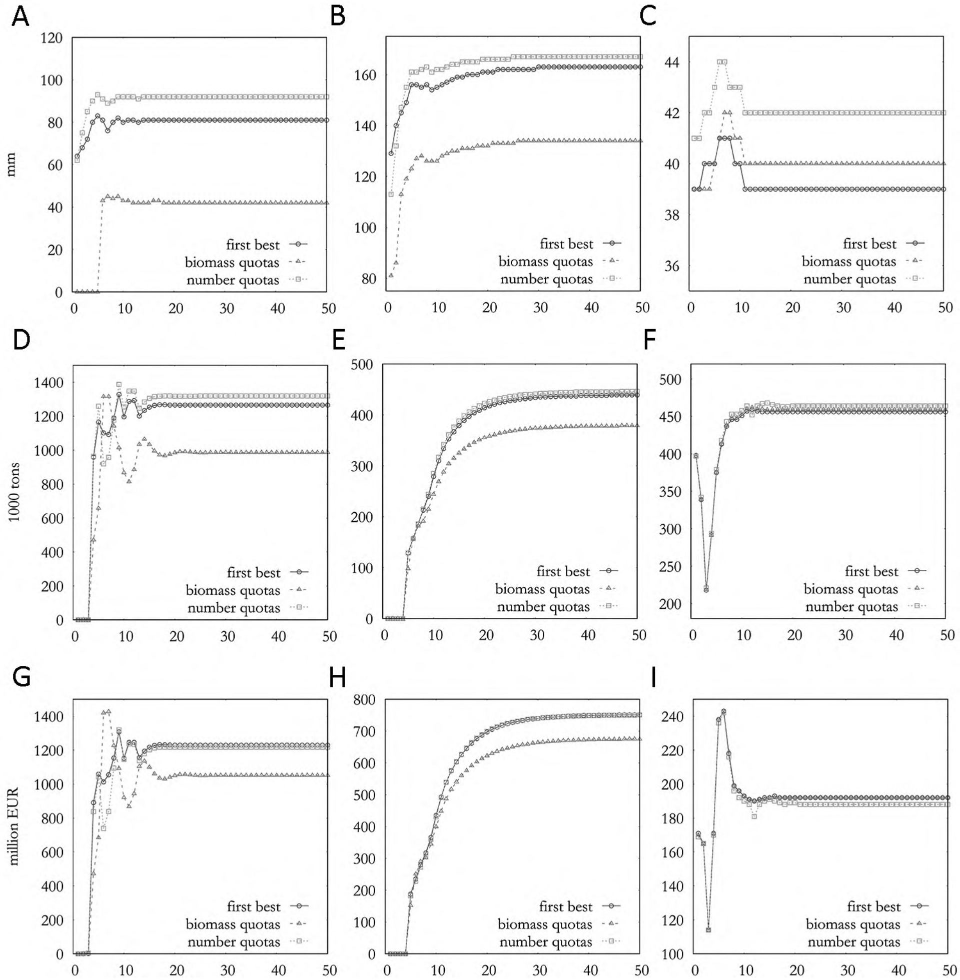

Figure 3. Mesh Size, Total Biomass Caught, and Annual Profits for the Three Empirical Examples. (A) NEAC mesh size. (B) EBC mesh size. (C) NEAM mesh size. (D) NEAC harvest. (E) EBC harvest. (F) NEAM harvest. (G) NEAC profit. (H) EBC profit. (I) NEAM profit. A color version of this figure is available online.

concave in the mesh size and fishing is profitable at all. Under these conditions, number quotas also result in a (weakly) larger mesh size than the socially optimal mesh size. The ranking is strict for interior solutions. We state these results formally as follows:

Proposition 3. If $\underline{\sigma} < \sigma^B < \bar{\sigma}$ and profit per fish $\frac{\pi(\sigma)}{N(\sigma)}$ is concave in mesh size, fishers choose a larger mesh size under number quotas than under biomass quotas,

$$\sigma^N > \sigma^B. \tag{23}$$

Similarly, if $\underline{\sigma} < \sigma^S < \bar{\sigma}$ and profit per fish $\frac{\pi(\sigma)}{N(\sigma)}$ is concave in mesh size, fishers choose a larger mesh size under number quotas than optimal,

$$\sigma^N > \sigma^S. \tag{24}$$

Proof. See online appendix B. □

EMPIRICAL EXAMPLES

We calibrate the model for three of the commercially important fisheries in the Northern Atlantic, namely the Northeast Arctic cod fishery (NEAC), the Eastern Baltic cod fishery (EBC), and the Northeast Atlantic mackerel fishery (NEAM). We chose these three examples based on economic relevance, availability of high quality data, and own scientific expertise.

Background. The Northeast Arctic cod fishery is the world's largest and most valuable cod fishery (Nakken 1994; Diekert 2013), sustaining catches of about 600,000 tons and generating a first-hand revenue (in Norway) of 7 billion NOK in 2018. Northeast Arctic cod may grow up to 170 cm large and weigh up to 50 kg, but the current minimum landing size is 44 cm and most fish that are caught weigh between 1.5 kg and 3 kg. Avoiding growth overfishing may thus yield important profits (Diekert et al. 2010).

Although we speak of mesh size when referring to selectivity, the key technical measures to protect young fish in this fishery is actually a sorting grid. Sorting grids in the codend of the trawl net are mandatory since 2007 (Sistiaga, Grimaldo, and Larsen 2008). Different versions of sorting grids may be used, but the legal minimum grid bar spacing is 55mm (Sistiaga et al. 2017). As the biological stock assessment model reports age-classes, we define a size class to correspond to one age-class. Moreover, we cap the number of size classes at $n = 13$ for Northeast Arctic cod, in correspondence with ICES (2016). All parameter values and further details on the calibration can be found in online appendix D.

The Eastern Baltic cod fishery has been the commercially most important fishery in the Baltic Sea. It has offered livelihood to a large proportion of fishers in the region. In 1980s the cod stock reached its historical record, and 22% of global cod catches were obtained from the Baltic Sea. One consequence of this economic contribution is the availability of exceptionally abundant scientific knowledge on various ecological features of the Baltic cod population along with fishing technology. The fishery has been managed by detailed gear regulations, seasonal closures, and minimum landing sizes, but the quotas have been set so generously that they have not been effectively restricting catch quantities for many years (Quaas et al. 2012). As a consequence, the stock and economic profitability declined. The Baltic cod fishery is thus a particularly interesting case to study if reversing priority in management, that is, setting restrictive quotas but abandoning detailed gear and landing-size prescriptions, could lead to a better outcome in economic terms.

In the Eastern Baltic cod fishery, fishers must choose between two codend configurations (EC 2010) that should protect young fish. We model the variant with a New Bacoma escape window in the codend (Feekings et al. 2013) as it is the most commonly used gear in the fishery.[6] The current minimum mesh size of the escape window is 120 mm (EC 2010). Following the biological stock assessment model (ICES 2014), we use $n = 8$ size classes for Eastern Baltic cod.

The Northeast Atlantic mackerel fishery is the most valuable pelagic fishery in the North Atlantic, generating a first-hand revenue of 2.5 billion NOK in Norway. The fish is highly migratory and straddles EU, Norwegian, Icelandic, and international waters, leading to a challenging governance situation (dubbed the "mackerel wars" by the media). Total catches in 2017 were about 1.2 million tons, exceeding the advised TACs by about 300,000 tons.

6. In a recent survey (EC 2013), 45 out of 66 interviewed fishers used a codend with a New Bacoma escape window.

Mackerel can grow relatively old (15 age classes are reported in the biological assessment report; ICES 2017), but growth in length and weight is limited (up to 50 cm and 500 grams). In contrast, there is an important size premium for larger fish.[7]

Results. We now present the first-best harvesting pattern for the three examples and contrast them to the second-best harvesting pattern under biomass quotas and number quotas, respectively. Details of the numerical solution procedure are described in online appendix C.

Table 1 shows the relative deviation of the second-best steady-state values from the first-best for the choice of selectivity (mesh size), total harvest (in terms of biomass), and profits.

The results highlight that number quotas may lead to a harvesting pattern that is much closer to the first-best than the harvesting pattern under biomass quotas for the two cod fisheries, while for the mackerel fishery, biomass quotas outperform number quotas. For the two cod fisheries, we find that steady-state profits under deregulated number quota management are only 0.1% to 1.1% below the theoretical optimum. In contrast, using biomass quotas would lead to losses between roughly 10% and 15%. For the mackerel fishery, both quota types come fairly close to the theoretical optimum, with number quotas leading to a loss of 2.1% and biomass quotas leading to a loss of 0.3%.

As we have shown theoretically, number quotas lead to an overly selective choice of the mesh size. For the mackerel fishery, mesh sizes are 7.3% too large in steady state, while they exceed the first-best steady state value by 13.5% in the Northeast Arctic cod fishery and by 2.5% in the Eastern Baltic cod fishery. To compensate for the resulting bias in the size structure of the harvest, the regulator increases the quota beyond the theoretically optimal total harvest.

Biomass quotas, in turn, are always less selective than number quotas. For the mackerel fishery, where the growth in price is steep, but growth in weight is flat and mortality is relatively high, biomass quotas still lead to an overly selective choice of mesh size (2.6% larger than the first-best mesh size). For the cod fisheries, however, biomass quotas lead to growth overfishing. In the Northeast Arctic cod fishery, mesh size choice under biomass quotas is 47% smaller than the first-best. In the Eastern Baltic cod fishery, mesh size under biomass quotas is 17.5% smaller than the first-best. In these cases, the regulator has to counteract the bias in the size structure of the harvest by reducing the quota relative to the first-best.

Figure 3 shows the time paths of selectivity (mesh or grid size in mm), total harvest (in 1,000 metric tons), and profits (million EUR 2012) for Northeast Arctic cod (NEAC, first column), Eastern Baltic cod (EBC, second column), and Northeast Atlantic mackerel (NEAM, third column). In all cases, the harvesting pattern settles on their respective steady-state values after about 20 years or less.

For the two cod fisheries we see that the mesh size values under number quotas are close to the first-best values, while the second-best mesh sizes under biomass quotas are significantly smaller. Consequently, the regulator restricts overall harvest to a much larger degree, which then leads to comparatively substantial reductions in profits. In contrast, quotas in terms of numbers would allow the regulator to set the TAC close to the optimal level, resulting in near-optimal profitability.

7. Fish below 350 grams receive, on average, a price of 5 NOK/kg, while fish above 400 grams receive average prices of about 9.5 NOK/kg.

Table 1. Deviations from First-Best Levels in Steady State

		Biomass Quotas (%)	Number Quotas (%)
Northeast Arctic cod	Mesh size	–47.2	13.5
	Total biomass caught	–22.1	4.2
	Profits	–14.6	–1.1
Eastern Baltic cod	Mesh size	–17.5	2.5
	Total biomass caught	–13.7	1.6
	Profits	–10.1	–0.1
Northeast Atlantic mackerel	Mesh size	2.6	7.3
	Total biomass caught	0.7	1.7
	Profits	–0.3	–2.1

For the mackerel fisheries, even the biomass quotas lead to overly selective mesh sizes, and number quotas lead to even larger mesh sizes. However, the resulting deviations from the first-best harvest levels are small and correspondingly the loss in profits is small as well.

DISCUSSION

The deviations of the second-best profits relative to their first-best levels could be interpreted as the costs of deregulating fishing gear choice. The question of whether these costs of deregulation outweigh the costs of enforcing gear restrictions remains an empirical issue that must be resolved at the level of a specific fishery. Here, our aim was to study the efficiency loss from deregulating gear choice in fisheries with individual quotas compared with first-best fishing. In particular, we study whether the costs of this liberalization could be limited by simply changing the "quota currency" from biomass to number quotas.

In line with the central tenet of modern fisheries economics to directly affect the incentives of the resource users (Wilen 2000), we develop a theory where the regulator sets an individual quota that constrains the harvest per fisher, while the fishers are free to choose gear selectivity as they like. Short of fully delineated individual quotas according to fish size, such an approach cannot reach the first-best optimal outcome (Costello and Deacon 2007; Quaas et al. 2013). Even under an accelerated technological progress in fine-tuned production technologies, it is not a realistic option to have fully delineated size-specific quotas. We have thus studied the question of whether it might be a good idea to issue quotas in terms of the number of fish instead of the weight of fish harvested.

Biological arguments suggest that measuring quotas (and catch) in terms of numbers of individual fish has several advantages: In biology, life-history theory has replaced population biomass approaches for a long time (Wilen 1985), recognizing that an individual fish is the biologically more meaningful unit than a kilogram of fish (Eikeset et al. 2013). A fish stock is made up of many individuals and it is the individual's recruitment, growth, and mortality that determines the overall stock dynamics. A kilogram of a mature fish has different properties than a kilogram of immature fish (Barneche et al. 2018), thus one needs to account for how the individuals grow and age to determine the fish stock's reproductive potential and to formulate adequate management policies (Tahvonen 2009; Tahvonen, Quaas, and Voss 2018). In fact, most scientific advice is given on the basis of biological models that first estimate the number of fish caught to then translate the model output in numbers back into a total allowable catch proposal that is given in terms of weight. Measuring quotas in terms of numbers would thus allow a much more direct way to give management advice that is immediately linked to the underlying relevant biological processes.

Measuring quotas in terms of numbers may reduce the problem of "growth overfishing"—catching fish too early before they have grown old and large (Diekert 2012). Growth overfishing is an economically and ecologically important problem in many commercial fisheries, where the systematic removal of young and small fish led to a severely distorted age- and size-structure of the fish stock, with destabilizing, and potentially irreversible, consequences for population dynamics (Anderson et al. 2008; Stenseth and Rouyer 2008). The intuition why number quotas may help is straightforward: a fisher has much stronger incentives to select for large fish when she or he has the right to catch a given number of individual fish, rather than the equivalent weight of fish. Currently, the problem of growth overfishing is curbed by supplementing quota management with command-and-control regulations. For example, there are several hundred EU regulations that are concerned in some way or other with the choice of fishing gear.[8] Such a detailed regulation of fishing gear is costly. The question is whether these additional command-and-control regulations remain necessary if quotas were measured in terms of numbers.

Measuring quotas in terms of numbers may also have disadvantages. There may be technical concerns of how fish could be counted. However, many fish are aligned one by one during the production process (usually when headed and gutted) and it should not be more difficult to count than to weigh at this point. Furthermore, a number of technologies exist today that are able to reliably count fish even in high-volume fisheries. In the Norwegian mackerel fishery, for example, flowmeters have been successfully used to count fish while pumping them on board the vessel. Current technological advances in areas such as machine vision and learning will further improve the ability to accurately measure what is harvested from the oceans.[9]

In addition, there may be institutional cost to changing the existing international framework. For historical reasons, international quotas are usually measured in terms of round weight and changing this would require international effort and negotiations. These transaction costs would have to be weighted against any potential benefits from a number-based quota system, but if the latter outweigh the former, there is, in principle, no reason why it should not be achievable to change this aspect of international fisheries management.

Number quotas may also induce incentives to be overly selective. Indeed, we have found that in theory, the ranking of number and biomass quotas in terms of welfare is not unique. We have thus studied this ranking question empirically for three commercially important fisheries. We find that for the Northeast Arctic and the Eastern Baltic cod fishery, number quotas fall short of the optimal steady-state profits by only 1.1% and 0.1%, while biomass quotas result in losses of 14.6% and 10.1%, respectively. For the Northeast Atlantic mackerel fishery, the ranking is reversed with number quotas implying a 2.1% reduction and biomass quotas implying a 0.3% reduction in steady-state profits.

Most importantly, the results from the detailed model confirm the insights gained from the simple model. It is essentially the relation between the mortality rate, the growth rate in weight,

8. Searching the term "gear" among all the texts in the EUR-Lex database that are in the collection "Fisheries Policy" returns 398 regulations and 303 proposals for regulations.

9. Still, there are limits to what can be reasonably achieved. Although there are some markets where being able to tell the full history of a given fish is important, traceability faces severe challenges in most mass-consumer markets as it would imply severe and costly changes to the production process. (A key problem in Norway, for example, is that fish from many small vessels are pooled before they are exported for packaging in China.)

and the increase in price that determines whether number quotas outperform biomass quotas in relation to the first-best harvesting pattern. These rates are relatively easy to calculate and their comparison allows a first-order estimate of whether quotas should be measured in terms of numbers in a given fishery.

Our model, though detailed, builds on a number of simplifying assumptions. First and foremost, we use an S-shaped selectivity curve as this selectivity pattern was empirically verified for the fisheries studied. For fisheries that use gill nets or longlines, a bell-shaped selectivity curve may be more appropriate. In previous studies that explicitly include both types of selectivity curves, this difference was of little consequence (Diekert et al. 2010). Nevertheless, working out the consequences of bell-shaped selectivity patterns and/or slot sizes for the ranking of biomass and number quotas is an interesting avenue for future work.

A concern with regard to implementing number quotas is a potential increase in the incentive to high-grade, that is, to discard small fish in order to fill the quota with larger fish. However, high-grading is a problem in fisheries with biomass quotas as well. Monitoring and enforcement, maybe even through full observer or camera coverage, would be needed under either quota system to enforce discard bans. Our argument is that enforcement efforts could be shifted away from gear inspections, not that enforcement is no longer needed.[10] Put differently, an increased incentive to circumvent a regulation is just a sign that the regulation is effective in creating rents and thus in increasing economic efficiency.

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