DUKE ENVIRONMENTAL ECONOMICS WORKING PAPER SERIES
organized by the
NICHOLAS INSTITUTE FOR ENVIRONMENTAL POLICY SOLUTIONS

Prices and Quantities to Control Overfishing

Martin D. Smith[*]
Sathya Gopalakrishnan[†]

Working Paper EE 11-07
July 2011

* Nicholas School of the Environment and Department of Economics, Duke University
† Nicholas School of the Environment, Duke University

Prices and Quantities to Control Overfishing

Martin D. Smith
Associate Professor of Environmental Economics
Nicholas School of the Environment
and Department of Economics
Duke University
Box 90328
Durham, NC 27708
marsmith@duke.edu

Sathya Gopalakrishnan
Assistant Professor (Starting September 1)
Department of Agricultural, Environmental, and Development Economics
The Ohio State University
Current Affiliation: Post-doctoral Fellow
Nicholas School of the Environment
Duke University
Box 90328
Durham, NC 27708
sg63@duke.edu

Abstract: Economists have long promoted fishery rationalization programs, but ITQs may fail to address the ecological consequences of fishing. Of particular concern is that economic incentives to harvest larger fish (due to size-dependent pricing or quota-induced discarding) can destabilize fish populations or lead to evolutionary changes. A substantial theoretical literature in economics has explored incentive problems in ITQ fisheries but has treated highgrading as part of the stock externality. We provide an alternative viewpoint in that the stock externality and the size-based incentives are two distinct externalities and thus require two distinct policy instruments. In this paper, we show that if managers know the price-by-size distribution and the size distribution of the population, total revenues and total catch (in weight) by vessel are sufficient statistics to design a schedule of revenue-neutral individualized landings taxes that eliminate the incentive to highgrade in an ITQ fishery. Landings taxes can be used to address the ecological consequences of fishing while using ITQs to address the open access stock externality.

Keywords: Individually Transferable Quotas, landings taxes, fish life history, highgrading, size-selective harvesting

JEL Codes: Q22

Prices and Quantities to Control Overfishing

Abstract: Economists have long promoted fishery rationalization programs, but ITQs may fail to address the ecological consequences of fishing. Of particular concern is that economic incentives to harvest larger fish (due to size-dependent pricing or quota-induced discarding) can destabilize fish populations or lead to evolutionary changes. A substantial theoretical literature in economics has explored incentive problems in ITQ fisheries but has treated highgrading as part of the stock externality. We provide an alternative viewpoint in that the stock externality and the size-based incentives are two distinct externalities and thus require two distinct policy instruments. In this paper, we show that if managers know the price-by-size distribution and the size distribution of the population, total revenues and total catch (in weight) by vessel are sufficient statistics to design a schedule of revenue-neutral individualized landings taxes that eliminate the incentive to highgrade in an ITQ fishery. Landings taxes can be used to address the ecological consequences of fishing while using ITQs to address the open access stock externality.

Keywords: Individually Transferable Quotas, landings taxes, fish life history, highgrading, size-selective harvesting

JEL Codes: Q22

Introduction

Economists have long extolled the virtues of fishery rationalization programs. Fisheries economists have particularly argued that Individually Transferable Quotas (ITQs) undo the main causal mechanism for fisheries overexploitation, namely the open access stock externality (Christy 1973; Grafton 1996). Landings taxes, though they have not been tried in a real fishery, are often discussed as having theoretical equivalence to tradable quotas in promoting efficiency; in a deterministic setting, landings fees and ITQs are comparable in the same way that there is equivalence between Pigouvian fees and cap and trade systems for pollution control (Wilen 1985; Hannesson 1991). The equivalence breaks down when there is uncertainty, and the familiar "prices versus quantities" discussion for pollution control becomes relevant for fisheries (Wetizman 1974; 2002). The recent pollution control literature acknowledges that there are circumstances in which a hybrid approach using both price and quantity instruments is useful (Murray, Newell and Pizer 2009). Our interest here is in whether there are circumstances in which both price and quantity instruments are called for in a deterministic setting due to unique features of the fishery.

One of the obstacles to widespread adoption of ITQs for fishery management is a lingering concern that these instruments fail to address the ecological consequences of fishing. Ecological impacts of fishing can stem from highgrading and discarding. That is, a quota owner has an incentive to fill his or her quota by targeting large, high-value fish and potentially discarding small, low-value fish. This incentive can exist regardless of whether individual quotas are tradable— as they are typically in Iceland, New Zealand, and increasingly in the U.S.— or non-tradable— as they are typically in Norway. Some mortality inevitably results from discarding, and both targeting and discarding can lead to a size distribution of harvested fish that is neither economically optimal nor biologically sustainable.

Although the severity of problems is a subject of debate and varies by fishery, the biological and ecological effects of size selective harvesting are extensive and well-documented. Concerns about size-selective harvesting include cases in which larger fish are more fecund (Palumbi 2004) or have increasing fecundity returns to size (Smith 2004), larger fish have more viable larvae (Berkeley et al. 2004), there is potential for sperm limitation in sequential hermaphrodites (Coleman et al. 1996), and there may even be evolutionary effects (Conover and Munch 2002). Guttormsen et al. (2008) show in a bioeconomic model how size-selective harvesting of a renewable resource can induce evolutionary changes. Their model adds conceptual basis for why the experimental results of Connover and Munch may be relevant for real-world fisheries.

A substantial theoretical literature in economics has explored incentive problems in ITQ fisheries (Anderson 1994,1995; Arnason 1994; Vestergaard 1996; Turner 1996; 1997; Hatcher 2005), but most of this literature has treated highgrading essentially as part of the stock externality. Our idea is most similar to the landings tax proposed in Anderson (1994) and the value-based ITQs introduced by Turner (1996). Based on a critical size, Anderson (1994) models a high- and low-value fish, whereas we allow for the distribution of fish sizes and prices to be continuous. In doing so, we relax Anderson's assumption of constant proportion of high- and low-value fish, which he argues is restrictive, and our model captures both targeting and discarding behavior. Turner (1996) proposes to solve the highgrading problem by delineating ITQs in terms of value rather than quantity. We provide an alternative viewpoint in that the stock externality and the size-based incentives are two distinct externalities and thus require two distinct policy instruments (Smith 2007) in the spirit of Tinbergen (1952).

We show that if managers know the price-by-size distribution and the size distribution of the population, total revenues and total catch (in weight) by vessel are sufficient statistics to design a schedule of revenue-neutral individualized landings taxes that eliminate the incentive to highgrade in an ITQ fishery. That is, landings taxes can be used to address the ecological consequences of fishing while using ITQs to address the open access stock externality. The information burden for managing with quotas and individualized taxes appears large at first blush, but all of the required information is already collected by federally managed fisheries in the U.S. and in many other parts of the world. The implication is that a focus on "prices versus quantities" in instrument choice

(Weitzman, 2002) may not be the central issue for fisheries. Instead, even in a deterministic world ecological factors necessitate both price and quantity instruments in some settings.

This paper first discusses evidence of size-based pricing and some of the incentives that it creates. The next section develops a model of individualized landings taxes. The final section discusses the policy implications and concludes.

Size-based pricing and incentives to truncate the size distribution of fish from below

Table 1 summarizes size-dependent prices for some common fish and shellfish. The fisheries span different places in the world, taxonomic groups, and production technologies (including aquaculture). The premiums for large fish vary by species, but they can be substantial. Perhaps largely due to a combination of recovery rates and quality, fish processors—and in some cases consumers—are often willing to pay more per weight for larger fish. This sample of fisheries is not a random sample but provides some anecdotal evidence that size-based pricing potentially creates incentives to discard or to target by size. Interestingly, the smallest premium in Table 1 is for large Norwegian farmed Atlantic salmon. This narrow price spread likely reflects the high degree of control in the salmon industry (Asche 2008), which effectively collapses the size distribution of slaughtered salmon into similar market categories.

A recent paper by Kristofersson and Rickertsen (2008) uses fishing micro data to test whether highgrading occurs in the Icelandic cod fishery. They specifically examine two different sources of highgrading: quota price-induced discarding and product price-induced discarding. They find evidence for product price-induced discarding but fail to reject the hypothesis of no quota price-induced discarding. The authors conclude that size-based product pricing leads to discarding because the hold capacity constraint binds. When the hold capacity constraint does not bind, a higher quota price theoretically can induce discarding because the marginal cost of landing fish is higher and vessels must compensate with higher marginal revenue.

In the modeling below, we are interested in the effects of product price on both targeting and discarding behavior. Successful targeting of larger fish does not waste fish in the sense that there is partial mortality of small fish that are thrown back; smaller fish simply are not caught. We would expect that this behavior puts more relative weight on the large portion of the size distribution of fish. Discarding, in contrast, places more weight on the large portion of the size distribution only to the extent that discarded smaller fish survive. If there is 0% mortality of discards, the relative weight on the larger portion of the size distribution is the same for targeting and discarding. As mortality increases, the amount of size selection decreases. However, conditional on the total landings being the same, discarding puts more pressure on the overall stocks relative to targeting. Thus, for concerns about evolutionary effects of size-selective harvesting, intensive selection on size under targeting behavior is arguably the greater concern.

A Simple Theoretical Model of Individualized Landings Taxes (ILTs)

Our focus in this paper is on product price-induced behavior. As such, our model describes a fishery with either of two institutional regimes: 1) ITQs in which hold capacity binds or 2) a fishery managed with non-transferable individual fishing quotas. Let t index time and i index individual fishing vessel. Suppose that each fishing vessel chooses overall fishing effort E_{it} and the share of effort devoted to either targeting or discarding (γ_{it}). We lump targeting and discarding together as we are primarily concerned with the effect on the size distribution of the population. For this simple model, one can think of this as representing discarding with no mortality. Let s index fish size. The function $x(s)$ represents the size distribution of the population (how many fish at each size converted to biomass units) with L_∞ denoting the terminal (maximum) size as in the standard von Bertallanfy growth model. Targeting effort γ_{it} influences the catchability of fish according to their age structure, reducing the catchability of young fish (age lower than $\bar{a}$) and increasing the catchability of big fish (age greater than $\bar{a}$)

$$(1) \qquad q_{it}(\gamma_{it}, a) = q^0[1+\gamma_{it}(1-e^{(\frac{\bar{a}-a(s)}{\bar{a}})})]$$

Thus, our model captures the realistic assumption of imperfect targeting; there is no knife-edge selectivity. Figure 1 illustrates the effect of targeting effort on the catchability by age class.

We assume a Schaefer production function such that harvest (H_{it}) is proportional to stock and effort with catchability (q_{it}), which depends on the level of share of effort devoted to targeting (γ_{it}):

$$(2) \qquad H_{it} = \int_0^{L_\infty} q_{it}(1-\gamma_{it})E_{it}x(s)ds.$$

Note that if the vessel chooses $\gamma_{it} = 0$, equation (2) reduces to the more familiar qEX, where X is the total stock and the catchability coefficient is constant over the entire size distribution. Applying von Bertallanfy growth and allometric parameters to the age-structured model flattens out the targeting intensity in size space (Figure 2). This tendency suggests that the modeling below will be more relevant for slow-growing fish. Fish that reach terminal length at an early age provide no incentives for targeting on the basis of age.

Figure 3 examines the relevance of age-based targeting for different von Bertallanfy coefficients.

When fish have size-dependent prices, revenue is a function of the size distribution of landed fish and not just total biomass. Suppose $p(s)$ is the distribution of price by size. Then total revenues R_{it} are:

$$(2)\qquad R_{it}(E_{it},\lambda_{it}) = \int_0^{L_\infty} q_{it}(1-\gamma_{it})E_{it}p(s)x(s)ds.$$

Suppose that the cost of effort is a constant c, the individual vessel's quota share is σ_{it}, and the total quota (by weight) in the fishery is Q_t. Note that we could also interpret $\sigma_{it}Q_t$ as hold capacity. The vessel's short-run profit maximization problem can then be written as:

$$(4)\qquad \max \Pi_{it}(E_{it},\gamma_{it}) = \int_0^{L_\infty} q_{it}(\gamma_{it})(1-\gamma_{it})E_{it}p(s)x(s)ds - cE_{it}$$

subject to

$$\begin{aligned}
&\int_0^{L_\infty} q_{it}E_{it}(1-\gamma_{it})x(s)ds \le \sigma_{it}Q_t && [\lambda]\\
&E_{it} \ge 0 && [\mu_1]\\
&\gamma_{it} \ge 0 && [\mu_2]\\
&\gamma_{it} \le 1 && [\mu_3]
\end{aligned}$$

Assuming a positive level of effort ($E_{it} > 0, \mu_1 = 0$) and positive harvest of fish (not all effort is devoted to highgrading ($\gamma_{it} < 0, \mu_3 = 0$), the associated necessary conditions are:

$$(5)\qquad \int_0^{L_\infty} q_{it}(1-\gamma_{it})p(s)x(s)ds - c - \lambda\int_0^{L_\infty} q_{it}(1-\gamma_{it})x(s)ds = 0$$

(6) $$\begin{aligned}&-\int_0^{L_\infty} q^0 \exp\left(\frac{\bar{a}-a}{\bar{a}}\right)E_{it}p(s)x(s)ds - 2\gamma_{it}\int_0^{L_\infty} q^0(1-\exp\left(\frac{\bar{a}-a(s)}{\bar{a}}\right)E_{it}p(s)x(s)ds \\ &+\lambda\left[\int_0^{L_\infty} q^0 \exp\left(\frac{\bar{a}-a}{\bar{a}}\right)E_{it}x(s)ds + 2\gamma_{it}\int_0^{L_\infty} q^0(1-\exp\left(\frac{\bar{a}-a(s)}{\bar{a}}\right)E_{it}x(s)ds\right] \le 0\end{aligned}$$

(7) $$\gamma_{it}\mu_2 = 0$$

The vessel will choose not to highgrade if the revenues from not highgrading exceed the opportunity cost of the quota:

(8) $$\int_0^{L_\infty} q_{it}E_{it}p(s)x(s)ds > \lambda\int_0^{L_\infty} q_{it}E_{it}x(s)ds$$

Otherwise, the vessel will devote positive effort to highgrading.

Suppose that the regulator wishes to eliminate highgrading such that fisheries draw from the entire size distribution of fish. Let $\bar{p}$ denote a target fleet-wide average price, where

(9) $$\bar{p} = \frac{\int_0^{L_\infty} p(s)x(s)ds}{\int_0^{L_\infty} x(s)ds}.$$

Figure 4 illustrates this fleet-wide price. The regulator can undo the incentive to highgrade in this setting by imposing an individualized landings tax (ILT):

(10) $\tau_{it} = \hat{p}_{it} - \bar{p}$, where

(11) $$\hat{p}_{it} = \frac{R_{it}}{H_{it}} = \frac{\int_0^{L_\infty} q_{it}E_{it}(1-\gamma_{it})p(s)x(s)ds}{\int_0^{L_\infty} q_{it}E_{it}(1-\gamma_{it})x(s)ds}$$

At first blush, the ILT might seem burdensome for the regulator. However, it is easily calculated from data that are already collected through landings tickets in federally regulated fisheries in the U.S. and in many other parts of the world. The regulator need only know the total quantity of fish landed and the total revenue. Knowledge of the price distribution is necessary to set $\bar{p}$ at the right level and can be obtained with a random sample of landings.

With the ILT imposed, the vessel's objective is now:

(12)
$$\begin{aligned}
&\max \Pi_{it}(E_{it},\gamma_{it}) = \int_0^{L_\infty} q_{it}(\gamma_{it})E_{it}[1-\gamma_{it}]p(s)x(s)ds - cE_{it} \\
&\qquad\qquad - \tau_{it}\int_0^{L_\infty} q_{it}(\gamma_{it})E_{it}[1-\gamma_{it}]x(s)ds \\
&\textit{subject to} \\
&\int_0^{L_\infty} q_{it}E_{it}(1-\gamma_{it})x(s)ds \le \sigma_{it}Q_t \qquad [\lambda] \\
&E_{it} \ge 0 \qquad [\mu_1] \\
&\gamma_{it} \ge 0 \qquad [\mu_2] \\
&\gamma_{it} \le 1 \qquad [\mu_3]
\end{aligned}$$

Substituting in the tax, we see that profits can be rewritten as:

(13)
$$\begin{aligned}
\Pi_{it}\left(E_{it},\gamma_{it}\right) &= \int_0^{L_\infty} q_{it}(\gamma_{it})[1-\gamma_{it}]E_{it}p\left(s\right)x\left(s\right)ds - cE_{it} \\
&\quad - \left(\frac{\int_0^{L_\infty} q_{it}(\gamma_{it})[1-\gamma_{it}]E_{it}p\left(s\right)x\left(s\right)ds}{\int_0^{L_\infty} q_{it}(\gamma_{it})[1-\gamma_{it}]E_{it}x\left(s\right)ds} - \bar{p} \right) \int_0^{L_\infty} q_{it}(\gamma_{it})[1-\gamma_{it}]E_{it}x\left(s\right)ds \\
&= \bar{p}\int_0^{L_\infty} q_{it}(\gamma_{it})[1-\gamma_{it}]E_{it}x\left(s\right)ds - cE_{it}
\end{aligned}$$

By inspection of equation (13), we can see that effort devoted to highgrading can only decrease profits. Formally, assuming a positive level of effort ($E_{it} > 0, \mu_1 = 0$) and positive harvest of fish (not all effort is devoted to highgrading ($\gamma_{it} < 0, \mu_3 = 0$), the associated necessary conditions are:

(14) $$\bar{p}\int_0^{L_\infty} q_{it}[1-\gamma_{it}]x(s)ds - c - \lambda\int_0^{L_\infty} q_{it}[1-\gamma_{it}]x(s)ds = 0$$

(15) $$\left(\lambda - \bar{p}\right)\left[\int_0^{L_\infty} q^0 \exp(\frac{\bar{a}-a}{\bar{a}})E_{it}x(s)ds + 2\gamma_{it}\int_0^{L_\infty} q^0(1-\exp(\frac{\bar{a}-a}{\bar{a}})E_{it}x(s)ds\right] + \mu_2 = 0$$

(16) $$\gamma_{it}\mu_2 = 0.$$

Equation (14) can only hold if $\bar{p} > \lambda$, which implies that the term before the braces in (15) is negative, and thus $\mu_2 > 0$. By equation (16), $\gamma_{it} = 0$. There is no effort devoted to highgrading.

Discussion

We find that the use of price and quantity instruments to control overfishing can be warranted even in a purely deterministic setting. The basic conclusion of our model is similar to Anderson (1994) and Turner (1996), and the cancellation that removes the incentive to highgrade in our model is analytically similar to theirs. The main differences are 1) that we allow for a continuous distribution of fish size, 2) we focus on product price-induced selectivity (rather than quota price-induced discarding), and 3) the ITQ in our model is a weight-based quota with an individual-level taxation scheme attached to it. In Anderson, the tax is for low- versus high-value fish, assuming that there is a fixed proportion of the two. In Turner, the two instruments are rolled into one as a value-based

ITQ. Managers with a value-based quota need to set a value-based TAC. With our combined ILT/ITQ instrument, the traditional role of stock assessment is preserved. Weight- based quotas can still be used with adjustments based on the total revenues landed. Whereas in Turner (1996), quota needs to be allocated either in dollar units or in weight-based units tied to relative prices. Neither of these follows clearly from standard stock assessment. Moreover, neither is particularly feasible when products are highly differentiated by size; the data requirements at the level of individual vessels are prohibitively high.

ITQs have become more politically palatable in recent years perhaps in part because they have been renamed "catch shares," but landings taxes present far greater political challenges. Is it worth attempting to put an ILT in place for a real-world fishery? The empirical evidence from Kristofersson and Rickertsen (2008) suggests that highgrading in Icelandic cod is present but not large. However, some experimental literature suggests that evolutionary impacts are a definite concern for fisheries managers (Conover and Much 2002). Guttormsen et al. (2008) show that the costs of regulation to combat size selection determine whether it is worth avoiding selection-induced evolutionary changes. The costs of implementing our proposed regulation within existing regulatory structures may be small, but the political costs almost certainly will be high.

To consider whether it is worth overcoming political barriers to taxation, we explore the potential for highgrading incentives in a real-world fishery, U.S. Pacific Northwest sablefish. We use twelve observations of size-dependent sablefish price in 2006 to fit a linear price equation. Sablefish are managed with ITQs in Alaska and are being considered for ITQ-based management in the Pacific Northwest, so it is worth asking whether an ITQ program should also include an ILT. The data come from the PACFIN database and represent sample means at three locations with between three and five size classes in each sample. Specifically, we use OLS to estimate price per kg (P) as a function of fish weight in kg (w): $P = 1.87\ (0.56) + 0.50\ (0.14) * w$. Standard errors are in parentheses, and the R^2 is 0.58. We can convert our size-dependent pricing into age-dependent pricing using von Bertallanfy growth and allometric parameters for sablefish. The results are in Figure 5, which provides a clue that the selection pressure on sablefish from targeting or discarding is likely present but not likely to be strong. The price premiums for larger fish are substantial. However, compared to many other long-lived fish, sablefish grow to near full size in a relatively short amount of time. There is an incentive to avoid fish below 10 years of age, but there is little incentive to target fish over, for instance, 40 years of age when the same premium would apply to a fish of age 20. This example illustrates that size selection may not always be significant enough to warrant an ILT even when size-dependent pricing is pronounced. A fruitful direction for future research is to explore other possible applications of an ILT in which selection pressure appears stronger and model the consequences of ILT-based management using an age-structured model.

An important caveat to our analysis is that we assume curtailing size-dependent targeting and discarding is desirable. This assumption is based on the ecological literature that highlights channels through which the presence of larger fish can increase productivity and resilience of fish populations. Nevertheless, it is an assumption and not the result of a bioeconomic optimization. A growing body of bioeconomic literature is examining the consequences of direct attempts to manage age-structure and fish life history (Smith, Zhang, and Coleman 2008; Huang and Smith 2009; Tahvonen 2009; Diekert et al. 2010, 2011; Diekert 2010; 2011; Quaas et al. 2011). Ignoring micro-incentives of fishermen in these models can lead to policy failures (Smith, Zhang, and Coleman 2008), but ignoring age structure will lead to different management targets altogether (Tahvonen 2009). All of these models share the feature that treating the stock as a monolithic biomass will miss something important and fail to produce the efficient pattern of harvest. Similar issues of insufficient delineation of ITQs in fisheries apply to spatial problems and within-season stock externalities (Boyce 1992; Sanchirico and Wilen 2005; Costello and Deacon 2007; Huang and Smith 2009).

In the age-structured bioeconomic literature, there is a sharp contrast between our approach and the approach in two recent working papers. Quaas et al. (2011) and Diekert (2010) conclude that setting ITQs in terms of numbers is superior to ITQs in terms of value when both recruitment and growth overfishing are at issue. Both argue that numbers-based quotas are feasible, but they would still be more information intensive than our combination of an ITQ with a landings tax. Most importantly, a numbers-based quota would intensify incentives to harvest larger fish due to size-based pricing, which is the exact opposite outcome of what our individual landings tax is trying to achieve; we are trying to undo the incentive to target larger fish. But neither Quaas et al. nor Diekert nest the ecological concerns that we discuss above: fecundity increasing returns to organism size, larval viability, and evolutionary changes. There appears to be a tension between protecting smaller fish, allowing them to grow to more valuable size classes and reach reproductive maturity, and protecting larger fish, essentially conserving the most valuable breeders in the population. These conflicting sets of policy advice highlight the need for more research on age-structured bioeconomic models and the delineation of economic instruments to control overfishing and generate economic value.

Acknowledgements

The authors thank the University of California, Santa Barbara for funding this research. The authors are grateful to Matt Turner for comments on an earlier version of this paper. The authors thank Frank Asche, Niels Vestergaard, the North Carolina Division of Marine Fisheries, and the Pacific States Marine Fisheries Commission for providing size-based pricing data.

References

Anderson, L.G. 1994. An Economic Analysis of Highgrading in ITQ Fisheries Regulation Programs. *Marine Resource Economics*. 9(3): 209-26.

Anderson, L.G. 1995. An Economic Analysis of Highgrading in ITQ Fisheries Regulation Programs: Errata. *Marine Resource Economics*. 10(1): 99-100

Arnason, R. 1994. On Catch Discarding in Fisheries. *Marine Resource Economics*. 9(3): 189-207.

Asche, F. 2008. Farming the sea. *Marine Resource Economics* 23:527-547.

Berkeley, S. A., C. Chapman, and S. M. Sogard. 2004. Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes melanops*. *Ecology* **85**:1258-1264.

Boyce, J.R. 1992. Individual transferable quotas and production externalities in a fishery. Natural Resource Modeling 6: 385-408.

Christy, F.T. 1973. Fisherman quotas: a tentative suggestion for domestic management. Occasional Paper 19 (Law of the Sea Institute, Rhode Island).

Coleman, F. C., C. C. Koenig, and L. A. Collins. 1996. Reproductive styles of shallow-water grouper (Pisces: Serranidae) in the eastern Gulf of Mexico and the consequences of fishing spawning aggregations. *Environ. Biol. Fishes* 47:129-141.

Conover, D.O. and S.B. Munch. 2002. Sustaining fisheries yields over evolutionary time scales. *Science* 297:94-96.

Costello, C. and R. Deacon. 2007. The efficiency gains from fully delineating rights in an itq fishery. *Marine Resource Economics* 22:347-361.

Diekert, F.K. 2010. Growth Overfishing. Conference of the International Institute for Fisheries Economics and Trade, Montpellier, France, July 2010.

Diekert, F. K., Hjermann, D. ., Naevdal, E., and Stenseth, N. C. 2010. Non-cooperative exploitation of multi-cohort fisheries—The role of gear selectivity in the North-East Arctic cod fishery. *Resource and Energy Economics* 32:78-92.

Diekert, F. K., Hjermann, D. ., Naevdal, E., and Stenseth, N. C. (2010). Spare the young fish: Optimal harvesting policies for north-east arctic cod, forthcoming, *Environmental and Resource Economics*.

Grafton, R.Q. 1996. Individual transferable quotas: theory and practice. *Reviews in Fish Biology and Fisheries* 6:5-20.

Guttormsen, A.G., D. Kristofersson, and E. Naevdal. 2008. Optimal management of renewable resources with Darwinian selection induced by harvesting. *Journal of Environmental Economics and Management* 56(2): 167-179.

Hannesson, R. 1991. From common fish to rights based fishing: Fisheries management and the evolution of exclusive rights to fish. *European Economic Review* 35:397-407.

Hatcher, A. 2005. On the Microeconomics of Quota Management in Fisheries. *Marine Resource Economics*. 20(1): 77-99.

Huang, L. and M.D. Smith. 2009. The dynamic efficiency costs of common-pool resource exploitation. In review.

Kristofersson, D. and K. Rickertsen. 2008 “Highgrading in quota-regulated fisheries: Evidence from the Icelandic cod fishery.” *American Journal of Agricultural Economics*.

Murray, B., R.G. Newell, and W.A. Pizer. 2009. Balancing cost and emissions uncertainty: An allowance reserve for cap and trade. *Review of Environmental Economics and Policy* 3: 84-103.

Quaas, M.F., T. Requate, K. Ruckesa, A. Skonhoft, N. Vestergaard, R. Voss. 2011. Incentives for Optimal Management of Age-Structured Fish Populations, Working Paper, University of Kiel.

Palumbi, S.R. 2004. Why mothers matter. *Nature* 430:621-22.

Sanchirico, J. N., and J. E. Wilen. 2005. Optimal Spatial Management of Renewable Resources: Matching Policy Scope to Ecosystem Scale. *Journal of Environmental Economics and Management* 50: 23-46.

Smith, M.D. 2004. Fishing yield, curvature, and spatial behavior: Implications for modeling marine reserves. *Natural Resource Modeling* 17:273-298.

Smith, M.D. 2007. "Individualized Landings Taxes (ILTs) to Eliminate Highgrading in an ITQ Fishery." Presentation. NCEAS Working Group on Property Rights in Fisheries, Santa Barbara, CA.

Smith, M.D., Zhang, J., Coleman, F.C., 2008. Econometric modeling of fisheries with complex life histories: avoiding biological management failures. *Journal of Environmental Economics and Management* 55: 265–280.

Tahvonen, O., 2009. Economics of harvesting age-structured fish populations. *Journal of Environmental Economics and Management* 58: 281–299.

Tinbergen, J. 1952. *On the theory of economic policy*. Amsterdam: North-Holland.

Turner, M. 1996. Value-Based ITQ's. *Marine Resource Economics*. 11(2): 59-69.

Turner, M. 1997. Quota-Induced Discarding in Heterogeneous Fisheries. *Journal of Environmental Economics and Management*. 33(2): 186-95.

Vestergaard, N. 1996. Discard Behavior, Highgrading and Regulation: The Case of the Greenland Shrimp Fishery. *Marine Resource Economics*. 11(4): 247-66.

Weitzman, M. 1974. Prices versus quantities. *Review of Economic Studies* 41: 477-91.

Weitzman, M. 2002. "Landing fees vs harvest quotas with uncertain fish stocks."*Journal of Environmental Economics and Management* 43(2):325-338.

Wilen, J.E. 1985. Towards a theory of the regulated fishery. *Marine Resource Economics* 1: 369-88.

Table 1 – Examples of size-dependent pricing of fish

Country	Species	Currency/unit	Year	Large	Medium	Small	Premium (Large vs. Small)	Note
Australia	Banana shrimp	AUD/kg	2006	12.69	9.35	7.59	67%	a
Denmark	Euopean Plaice	DKR/kg		20.31	21.46	12.46	63%	b
Denmark	Atlantic Cod	DKR/kg		28.18	25.67	19.59	44%	c
Denmark	Common Sole	DKR/kg		81.82	58.06	47.84	71%	d
Egypt	Tilapia	EGP/kg	2006	8.68	5.87	3.76	131%	e
Iceland	Cod	ISK/kg	1998-2001	151.20	124.90	105.70	43%	f
Iceland	Saithe	ISK/kg	2006	59.67		49.73	20%	g
Norway	Cod	NOK/kg	2006	22.28	20.06	16.89	32%	h
Norway	Salmon	NOK/kg	2006?	32.19	32.17	29.44	9%	i
Spain	Hake	EUR/kg	2005	17.93	13.12	8.47	112%	j
United States	Sablefish	USD/lb	2006	1.82	1.52	1.26	45%	k
United States	Brown shrimp	USD/lb	2005	2.53	2.30	1.07	137%	l

Notes and sources:

a Frank Asche, University of Stravanger (personal communication)

b Niels Vestergaard, University of Southern Denmark (personal communication)
Large is > 0.6 kg/fish, medium is 0.4-0.6 kg/fish, and small is 0.15-0.3 kg/fish.

c Niels Vestergaard, University of Southern Denmark (personal communication)
Large is > 7 kg/fish, medium is 4-7 kg/fish, and small is 1-2 kg/fish.

d Niels Vestergaard, University of Southern Denmark (personal communication)
Large is > 0.5 kg/fish, medium is 0.35-0.5 kg/fish, and small is 0.25-0.35 kg/fish.

e Frank Asche, University of Stravanger (personal communication)
Collected at El Obour market. Tilapia large is 1-5 fish/kg, medium is 6-12 fish/kg, and small is 13-25 fish/kg.

f Large, medium, and small mean prices for longline cod from Kristofersson and Rickertsent (2008).

g Frank Asche, University of Stravanger (personal communication)

h Frank Asche, University of Stravanger (personal communication)

i Frank Asche, University of Stravanger (personal communication)
Aquacultured salmon (exlcludes small sizes that are not normal market categories.
Large is 6-7 kg/fish, medium is 4-5 kg/fish, and small is 2-3 kg/fish.

j Frank Asche, University of Stravanger (personal communication)
Original source Spanish Ministry of Agriculture, Fisheries and Food

k Pacific States Marine Fisheries Commmision.
Sablefish harvest from U.S. west coast (excluding Alaska)

l North Carolina Department of Environment and Resources, Divsiion of Marine Fisheries.
Mean price in August 2005 large (15-20 per pound), medium (36-40 per pound), and small (60-70 per pound).

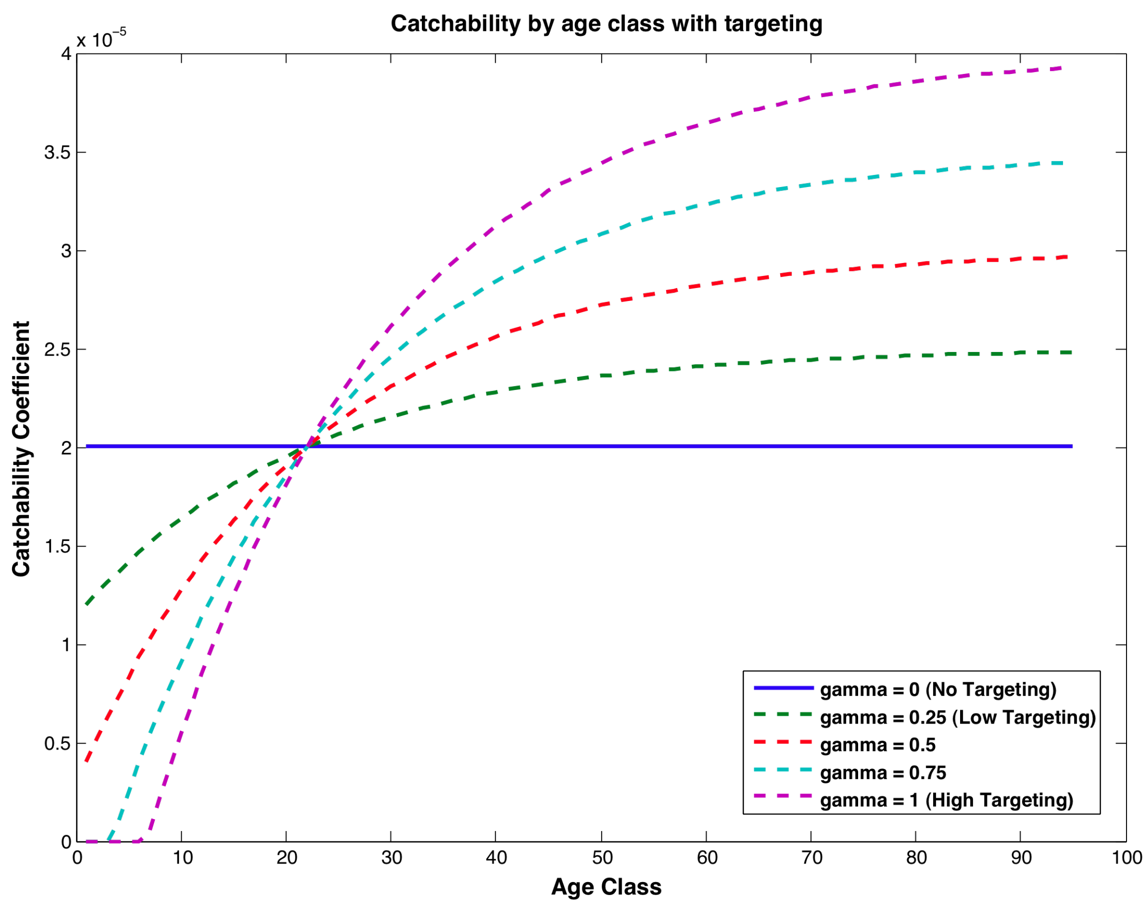

Figure 1. Highgrading effort increases the catchability of big fish and decreases the catchability of smaller fish. As vessels allocate more effort to targeting large fish (increasing γ_{it}), they increase the catchability of bigger fish (fish that are larger than size class $\bar{a}$) and alter the size distribution (*s*). This leads to harvesting more biomass from the upper portion of the biomass distribution *x(s)*.

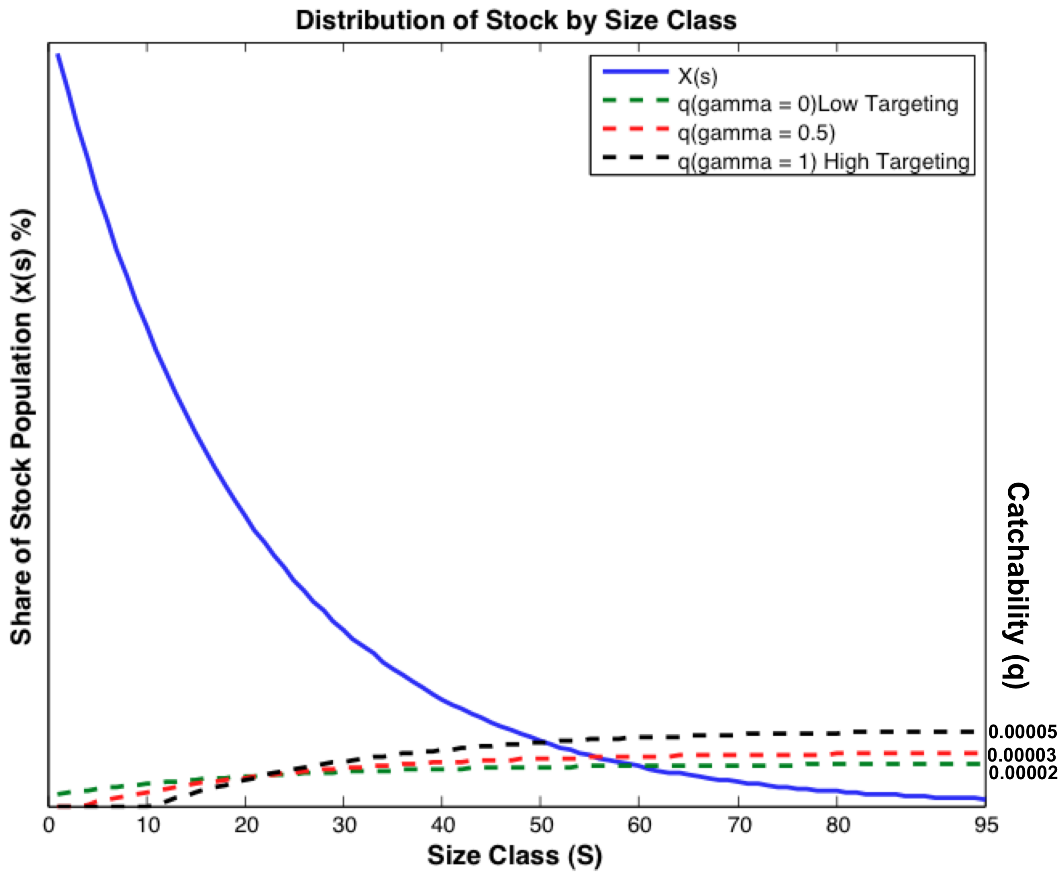

Figure 2. Distribution of Stock and catchability by size class. Applying von Bertallanfy growth and allometric parameters to the age-structured model flattens out the targeting intensity in size space.

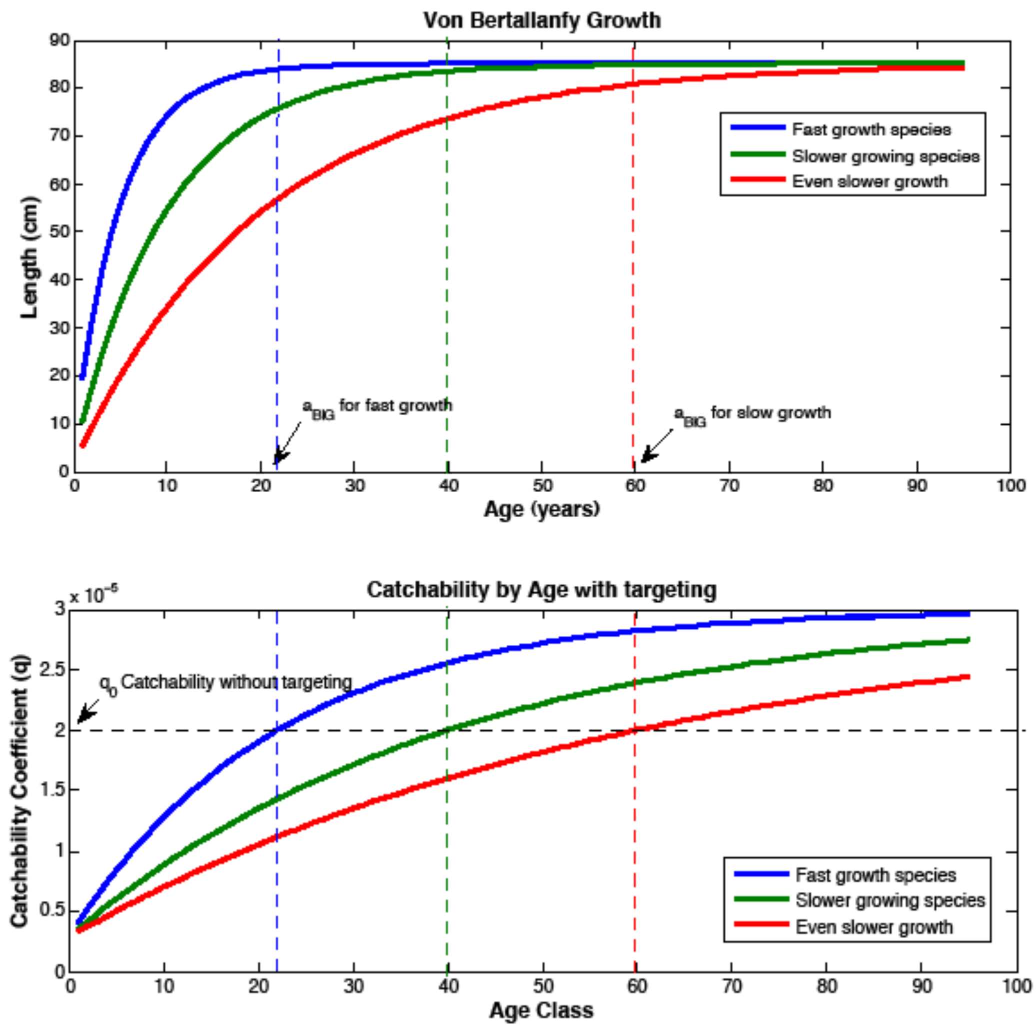

Figure 3. Growth and targeting in the age-based model. The effective targeting in an age-based model depends on the von-Bertallanfy growth curve. For slower growing species, rotating the catchability distribution is more relevant for older fish.

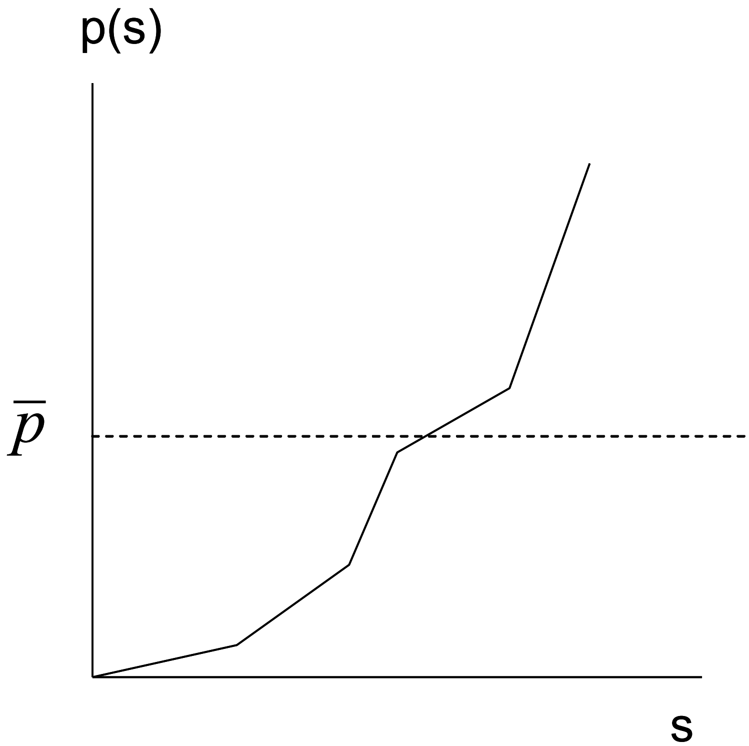

Figure 4. Fleet-wide target price. When prices are size-dependent, fleet-wide target price is the weighted average of the price distribution.

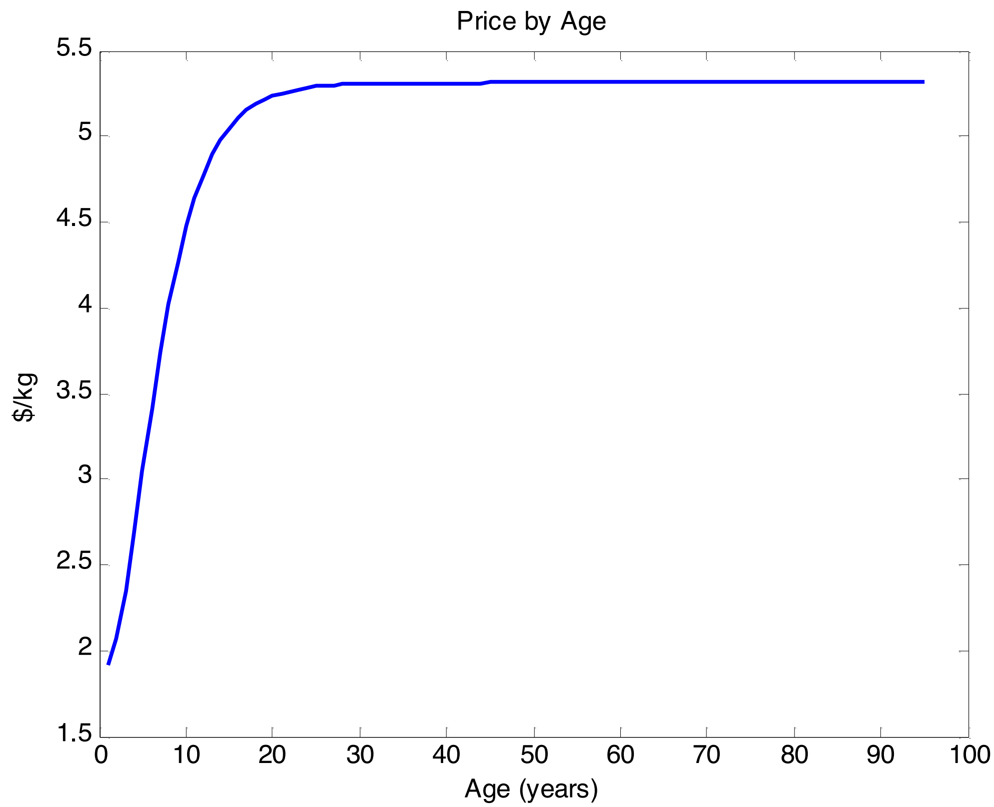

Figure 5. Price of sablefish as a function of age. Uses OLS estimates of size-dependent pricing and converts to age-dependent pricing using von Bertallanfy growth and allometric parameters specific to sablefish.