High-Grading in a Quota-Regulated Fishery, with Empirical Evidence from the Icelandic Cod Fishery

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Abstract
Fishers in quota-regulated fisheries find it to their advantage to discard less valuable fish at sea to increase the value of their catch. A theoretical model describing the high-grading behavior of fishers is presented, and an empirical model is derived as well as a testing strategy to test for high-grading and to estimate the discarded amount of each grade. The model is applied to data for the Icelandic quota regulated cod fishery during the period September 1998 to June 2001. The results indicate that high-grading occurs in the Icelandic cod fishery for both long-line and net vessels. However, the discard rates are small, and the results clearly suggest that the ban on discards in Iceland has effectively dealt with high-grading. The estimated discard rates are consistent with existing estimates of high-grading for the same types of vessel in the same fishery. This suggests that the modeling of discarding decisions based purely on incentives is a useful alternative to classical biometric methods.

Keywords: ITQ’s, highgrading, empirical estimation.

JEL Q21, Q22, C12

Introduction
Fishers generally are unable to limit their catch completely according to their wishes owing to the wide variety of different species and grades of fish that occupy the same habitat. As fishing is an economic activity and fishers maximize their own gain, they find it to their advantage to discard fish that do not add to profits. High-grading is the practice of limiting landings to more valuable grades of a targeted species by discarding the less valuable ones at sea. The mortality rate of discarded fish is high (Palsson, Einarsson and Bjornsson 2003), and discarding involves the following social costs: the market value of the fish is lost, the effort used to harvest the fish is wasted, and the reproductive potential of the fish is wasted (Pascoe 1997).

Anderson (1994 a and b), Arnason (1994) and Turner (1997) show how Individual Transferable Quotas (ITQ’s) can induce high-grading. The value of the quota becomes an additional cost item associated with landing the fish. The quota price can be high compared to the landed value of the fish and creates a considerable incentive to discard less valuable grades. The social planner can respond to ITQ-induced high-grading by banning it, as, for example, Iceland and Norway have done. For the ban to be effective, there must be some punishment for violation and a monitoring system to catch violators. Turner (1997) points out that shipboard monitoring is very expensive. The social planner must decide on the optimal monitoring strategy. If the monitoring strategy is too relaxed, high-grading will not be adequately discouraged. If it is too strict, monitoring costs will be excessive. If the social planner is to take the correct decision, it is crucial for him to assess the extent of the problem.

The incentives to high-grade are economic, and economic models of the behavior of fishers can be used to describe it. The model presented in the paper is a modification of the models of Arnason (1994), Vestergaard (1996) and Turner (1997). Rather than assuming that fishers have no control over what they catch, I assume that they can choose gear but not the composition of their catch given gear choice. In the aforementioned studies, it is assumed that fishing costs are linear in discarding. This leads to the corner or so-called bang–bang solution, where either all or none of each grade of fish is discarded. However, the bang–bang solution is not supported by empirical estimates of discarding in fisheries where discarding is banned (McBride and Fotland 1996, Palsson Schopka, and Einarsson. 2003). It seems rather that fishers choose internal solutions, with positive but not maximal discards of lower grade fish. Such bans typically include special schemes to catch serious offenders, as well as progressive penalties for violations. This implies an increasing marginal discarding cost. Furthermore, input use per unit output is not fixed in fishing, owing to factors like the increasing weight of the vessel as the hold is filled. It is important to take these two nonlinear cost components into account when analyzing high-grading.

The contributions of this paper are threefold. First, I derive a model describing the high-grading behavior of fishers, taking into account the nonlinear discard and effort cost. Fishing technology is defined in a way that facilitates empirical estimation. Second, I devise a testing strategy to test for high-grading and to estimate the discarded amount of each grade. Third, I apply the empirical model to data from the Icelandic ITQ-regulated cod fishery during the period from September 1998 to June 2001. The estimates are compared to existing estimates of high-grading in the Icelandic cod fisheries for verification.

Model

The model is defined in a similar way to the models of Turner (1997) as well as that of Arnason (1994) and Vestergaard (1996). The focus is on individual fishers, and the model describes their operating decisions, including the decision to discard. It is assumed that a fisher maximizes profit for each fishing trip and participates in a single species fishery where his/her catch is composed of n grades. Only slight modifications to the model are necessary for it to describe a multispecies fishery. I make three modifications to the model, regarding the effects of gear choice, the definition of technology and discarding cost. It is common to assume that the fisher has no control over the grade composition of the catch. However, fishers can choose their gear, which affects catch composition. Palsson et al. (2003) estimate that while long-line vessels discard 1.0% of their landings of cod, Danish seine vessels discard 7.6%. Differences in discard rates between vessel types are also reported by Stratoudakis et al. (1999) and Stratoudakis et al. (1998). The problem of gear choice can be overcome empirically as typically only a handful of gear types are used for fishing for each species and considerable investment is involved in changing gear. Gear choice is not a trip-to-trip decision but rather one that is taken once in the lifetime of a vessel. I assume therefore that gear has already been chosen, and the model only determines the amount of input use and discards given the choice of gear. Furthermore, instead of defining effort as a decision variable, I define a production function. This is the more general way of defining technology that lends itself more easily to empirical estimation. According to the model, the fisher has two decision variables, input use (x) and discard of grade i (d_i)[i]. I assume only one input, x, for simplicity. Landings of grade i are described by the following equation:

$$y_i = a_i y(x) - d_i \tag{1}$$

where y_i is the landings of size grade i, $y(x)$ is the total catch given inputs, x represents inputs, d_i is the discard of grade i, a_i is the catch proportion of grade i in the total catch $y(x)$ and $\Sigma_i a_i \equiv 1$. The total catch function, $y(x)$, is assumed to have the following properties.

$$\begin{aligned} \frac{\partial y(x)}{\partial x} &= y_x(x) > 0 \\ \frac{\partial^2 y(x)}{\partial x^2} &= y_{xx}(x) < 0 \end{aligned} \tag{2}$$

The third modification regards the definition of discarding cost. Assume that discarding is illegal and that the penalty is monetary, in the form of a fine. This implies a progressive discarding cost function: the more discarded, the larger the punishment and the probability of getting caught. I make the simplifying assumption that the cost of discarding is associated with total discards and not the discards of each grade. This is perfectly plausible for a single species fishery as it is no more expensive to throw a 1 kg cod overboard than a 2 kg one, and the fines are based on total discards and not the discards of any single grade. The discarding cost function, $C(D)$, is assumed to have the following properties:

$$\begin{aligned} \frac{\partial C(D)}{\partial d_i} &= \frac{\partial C(D)}{\partial D}\frac{\partial D}{\partial d_i} = \frac{\partial C(D)}{\partial D}\frac{\partial \sum_i d_i}{\partial d_i} = \frac{\partial C(D)}{\partial D} = C_D(D) > 0 \\ \frac{\partial^2 C(D)}{\partial d_i^2} &= \frac{\partial^2 C(D)}{\partial d_i \partial d_j} = \frac{\partial^2 C(D)}{\partial D^2} = C_{DD}(D) > 0 \end{aligned} \tag{3}$$

where D represents total discards ($\Sigma_i d_i = D$).

I further assume that price differs by grade and that there are three cost categories: input cost, discard cost and landing cost. I assume that the fishery is managed by an ITQ and that there is a functioning quota market where unlimited amounts of quota can be traded (relative to the daily needs of a single vessel). The model can easily be adapted to other management schemes such as open access, nontradable quotas and total allowable catch.

The fisher is assumed to maximize the per trip profit given by:

$$\max_{x,d_i} \pi(x,d_i) = \sum_i \left[p_i y_i - c_l y_i - w_{ITQ} x_{ITQi} \right] - wx - C\left(\sum_i d_i\right) - F \tag{4}$$

where p_i is the price of size grade i, d_i is the quantity discarded of grade i, c_l is the per unit cost of landing, w_{ITQ} is the unit price of quota, w is the input price, $C(\Sigma_i d_i) = C(D)$ is the discarding cost function and F is fixed cost. To simplify the problem we can use the definition of landings in (1) and the fact that quota use must equal landings $x_{ITQi} = y_i$. Substitution results in:

$$\max_{x,d_i} \pi(x,d_i) = \sum_i \left[\left(p_i - c_l - w_{ITQ}\right)\left(a_i y(x) - d_i\right) \right] - wx - C(D) - F\ . \tag{5}$$

The model is subject to the following restrictions:

$$\sum_i \left(a_i y(x) - d_i\right) \le B \tag{6}$$

where B is the hold size. The restriction simply states that the fisher cannot land more in each trip than what the vessel can carry.

Two restrictions set the upper and lower levels of allowable discards. First, the fishers cannot discard more than they catch.

$$a_i y(x) - d_i \ge 0 \tag{7}$$

Second, they cannot discard less than nothing.

$$d_i \ge 0 \tag{8}$$

The Lagrangian for the fisher's per trip maximization is as follows.

$$\begin{aligned} L = {} & \sum_i \left[\left(p_i - c_l - w_{ITQ}\right)\left(a_i y(x) - d_i\right) \right] - wx - C(D) - F \\ & + \sum_i \left[\lambda_{0i}(d_i) \right] + \sum_i \left[\lambda_{1i}\left(a_i y(x) - d_i\right) \right] + \lambda_2 \left[B - \sum_i \left(a_i y(x) - d_i\right) \right] \end{aligned} \tag{9}$$

First-order conditions, after some simplification using $\Sigma_i a_i \equiv 1$, are as follows.

$$\frac{\partial L}{\partial x} = \sum_i \left(\left(p_i - c_l - w_{ITQ}\right) a_i y_x(x) \right) - w + \sum_i \lambda_{1i}\left(a_i y_x(x)\right) - \lambda_2 y_x(x) \le 0 \tag{10}$$

$$\frac{\partial L}{\partial d_i} = -\left(p_i - c_l - w_{ITQ}\right) - C_D(D) + \lambda_{0i} - \lambda_{1i} + \lambda_2 \le 0 \tag{11}$$

In addition we have the following complementary slackness conditions.

$$x\frac{\partial L}{\partial x} = 0,\ d_i \frac{\partial L}{\partial d_i} = 0,\ \lambda_{0i}(-d_i) = 0,\ \lambda_{1i}\left(a_i y(x) - d_i\right) = 0,\ \lambda_2 \left(B - \sum_i \left(a_i y(x) - d_i\right) \right) = 0$$

$$\lambda_{0i} \ge 0,\ \lambda_{1i} \ge 0,\ \lambda_2 \ge 0 \tag{12}$$

There are a number of solutions to the model, depending on whether the Lagrange multipliers are zero or positive. A full set of solutions is available from the author upon request. I will only show two solutions that best fit the empirical evidence for high-grading behavior. According to the analysis of Palsson et al. (2003), there is some but not full discarding of the least valuable grades and no discarding of others. I present these solutions with and without a binding hold constraint. Assume that I is the set of all grades, J is the set of grades with positive discarders and K is the set of nondiscarded grades such that $i \in I$, $j \in J$, $k \in K$, $I = J \cup K$, $J \cap K = \varnothing$. This indicates that the Lagrange multipliers are $\lambda_{0j} = 0, \lambda_{0k} > 0, \lambda_{1i} = 0$.

First, we will assume that the fisher is not restricted by the hold constraint ($\lambda_2 = 0$). The rule determining the profit maximizing effort is found directly from the first order conditions in (10).

$$\begin{aligned}&\sum_i\left(\left(p_i - c_l - w_{ITQ}\right)a_i y_x\left(x\right)\right) - w = 0\\&\sum_i\left(p_i a_i\right) = \frac{w}{y_x\left(x\right)} + c_l + w_{ITQ}\end{aligned} \tag{13}$$

The effort rule is the well-known rule of production economics that marginal cost should equal marginal revenue. Note that the marginal revenue is the average price of the fish that is caught. The first term on the cost side deserves a comment as it reappears in a later solution. It is the input price over the marginal product or the input cost of the marginal unit produced.

The discarding rule for discarded grade *j* results directly from (11).

$$\begin{aligned}&p_j - c_l - w_{ITQ} + C_D\left(D\right) = 0\\&w_{ITQ} + c_l = p_j + C_D\left(D\right)\end{aligned} \tag{14}$$

At the optimal discard quantity, marginal revenue, comprised of the quota price plus the landing cost that is not incurred if the fish is discarded, should equal the marginal cost, comprised of the price of the fish plus the marginal discarding cost. The rule clearly indicates that the higher the quota price, the larger the quantity of discards. Furthermore, it shows that the lower the price of the grade, the larger the quantity of discards. If we assume that the discarding cost is constant, this would lead to a bang–bang solution where either all or none of the fish is discarded.

The discarding rule for nondiscarded grade *k* from (11) is as follows.

$$\begin{aligned}&-\left(p_k - c_l - w_{ITQ}\right) - C_D\left(D\right) + \lambda_{0k} = 0\\&\lambda_{0i} = p_k + C_D\left(D\right) - \left(w_{ITQ} + c_l\right)\end{aligned} \tag{15}$$

No discarding will occur as long as the price plus marginal discard cost exceeds the landing and quota costs.

Let us look at the second solution, with a binding hold constraint. The cost of a fishing vessel depends on its size. It is therefore probable that the hold constraint is often binding in real life. For this solution, we assume, as before, that we have some but not full discarding of the least valuable grades and none of others with a binding hold constraint. The Lagrange multipliers will meet the following requirements: $\lambda_{0j} = 0, \lambda_{0k} > 0, \lambda_{1i} = 0, \lambda_2 > 0$.

As the hold constraint is binding, the per-trip landings are set. We only need to identify the discarding rule. First, we solve (10) for the hold constraint multiplier.

$$\begin{aligned}&\sum_i\left(\left(p_i - c_l - w_{ITQ}\right)a_i y_x\left(x\right)\right) - w - \lambda_2 y_x\left(x\right) = 0\\&\lambda_2 = \sum_i\left(p_i a_i\right) - \frac{w}{y_x\left(x\right)} - c_l - w_{ITQ}\end{aligned} \tag{16}$$

We can substitute (16) into the first-order contribution for discarded grade *j*, in (11) which becomes as follows.

$$\begin{aligned}&-\left(p_j - c_l - w_{ITQ}\right) - C_D\left(D\right) + \lambda_2 = 0\\&\lambda_2 = \left(p_j - c_l - w_{ITQ}\right) + C_D\left(D\right)\\&\sum_i\left(p_i a_i\right) - \frac{w}{y_x\left(x\right)} - c_l - w_{ITQ} = p_j - c_l - w_{ITQ} + C_D\left(D\right)\\&\sum_i\left(p_i a_i\right) = p_j + \frac{w}{y_x\left(x\right)} + C_D\left(D\right)\end{aligned} \tag{17}$$

The discarding rule has changed considerably. The marginal revenue of discarding is the average price of the fish that is caught to replace the discarded fish. Neither the quota price nor the landing cost is included in (17), as one unit of fish is exchanged for another while the landings remain unchanged.

The marginal discarding cost consists of the price of the discarded fish, the marginal discarding cost and the marginal input cost per unit output. This is the cost of fishing one unit of catch to replace the discarded one. The important variables now are clearly the prices of different grades and inputs, as it is price differences that create the incentives to high-grade. The difference between the discarding rule in (15) and the one in (17) has an empirical implication. Input price rather than quota price affects high-grading if the holding constraint is binding, and vice versa if the hold constraint is not binding.

The discarding rule for nondiscarded grade k from (16) and (11) is as follows.

$$-p_k - C_D\left(D\right) + \lambda_{0i} + \sum_i \left(p_i a_i\right) - \frac{w}{y_x\left(x\right)} = 0$$
$$\lambda_{0k} = p_k + C_D\left(D\right) + \frac{w}{y_x\left(x\right)} - \sum_i \left(p_i a_i\right) \tag{18}$$

Grade i will not be discarded as long as the marginal cost of discarding it exceeds the marginal revenue of the next unit caught.

Empirical implementation

The solution to the maximizing problem in equations (13) through (18) is determined by the prices of inputs and outputs. Let **p** be the vectors of prices of different grades of fish, p_i, and let **w** be the vector of input and quota prices, w and w_{ITQ}. Let the discard cost function be described by a parameter vector $\boldsymbol{\theta}$, such that $C\left(D\middle|\boldsymbol{\theta}\right)$. The solution will take the following form:

$$x_k^* = x_k\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) \tag{19}$$

where x_k is either the input, x, or the quota use, x_{ITQ}.

$$d_i^* = d_i\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) \tag{20}$$

$$y_i^* = y_i\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) \tag{21}$$

Replacement of equations (19) and (21) into the original problem in (4) results in the profit function:

$$\boldsymbol{\Pi}\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) \equiv \max_{\mathbf{x},\mathbf{d}} \left\{\mathbf{p}'\mathbf{y}^* - c_l \mathbf{1}'\mathbf{y}^* - \mathbf{w}'\mathbf{x}^* - C\left(D^*\middle|\boldsymbol{\theta}\right) - F \middle| \mathbf{x},\mathbf{d} \text{ feasable}\right\} \tag{22}$$

where **y, d** and **x** are vectors of the y_i, d_i and x_k variables. The output supply and input demand functions can be derived from the profit function (22) by Hotellings lemma.

$$\frac{\partial \boldsymbol{\Pi}\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right)}{\partial p_i} = y_i^* \tag{23}$$

$$\frac{\partial \boldsymbol{\Pi}\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right)}{\partial w_k} = -x_k^* \tag{24}$$

Tests

We would like to test the hypothesis that there is no high-grading in the fishery. One way to achieve this is to use the definition of landings in (1).

$$y_i^* = a_i y\left(x\right) - d_i \tag{25}$$

If no high-grading occurs, then:

$$d_i \equiv 0. \tag{26}$$

This implies the following property of the output supply functions defined in (21) and (23).

$$y_i^*\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) = a_i y\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right) \tag{27}$$

Given that our null hypothesis is true, the following must hold.

$$\frac{\partial \boldsymbol{\Pi}\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right)}{\partial p_i \partial p_k} = \frac{\partial y_i^*\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right)}{\partial p_k} = a_i \frac{\partial y\left(\mathbf{p}, \mathbf{w}, \boldsymbol{\theta}\right)}{\partial p_k} \tag{28}$$

The output shares are estimated by average landings given that there is no high-grading:

$$\frac{\overline{y}_i}{\overline{y}} = \hat{a}_i \tag{29}$$

where $\overline{y}_i$ is the average landings of grade i and $\overline{y}$ is total average landings. Let:

$$\frac{\partial y(\mathbf{p},\mathbf{w},\boldsymbol{\theta})}{\partial p_k} = y_{p_k}\,. \tag{30}$$

Then the matrix of second derivatives of the profit function (23) must have the following property.

$$\begin{bmatrix} \hat{a}_i y_{p_k} & \cdots & \hat{a}_i y_{p_K} \\ \vdots & \ddots & \vdots \\ \hat{a}_I y_{p_k} & \cdots & \hat{a}_I y_{p_K} \end{bmatrix} = \begin{bmatrix} \hat{a}_i \\ \vdots \\ \hat{a}_I \end{bmatrix} \begin{bmatrix} y_{p_k} & \cdots & y_{p_K} \end{bmatrix} \tag{31}$$

Equation (31) is a parametric restriction that is testable for an empirical model[ii].

We can further test if the quota and input prices induce high-grading. This would provide information on the extent to which the hold constraint is binding. The results of the tests may help in choosing appropriate policy. The test is formulated in the same way as the no-high-grading hypothesis. If quota price does not influence high-grading, then:

$$\frac{\partial d_i(\mathbf{p},\mathbf{w},,\boldsymbol{\theta})}{\partial w_{ITQ}} \equiv 0\,. \tag{32}$$

Equation (32) indicates that the derivative of the supply functions with respect to quota price is as follows.

$$\frac{\partial y_i^*(\mathbf{p},\mathbf{w},\boldsymbol{\theta})}{\partial w_{ITQ}} = a_i \frac{y(\mathbf{p},\mathbf{w},\boldsymbol{\theta})}{\partial w_{ITQ}} \tag{33}$$

Equation (33) is a testable parametric restriction. Exactly the same arguments can be used to derive a test if other input prices, w, affect discarding. Note that the system of output supply and all input demand equation, in (23) and (24), is symmetric. The tests must be constructed in such a way that symmetry is imposed on the null hypothesis.

Estimated discards

Given that we have high-grading, we can use the model to estimate the level of discards of each grade under any pricing. The estimated discards can be used in the test, as we have clear expectations with respect to which grades are discarded; i.e., the least valuable ones. This should be the prediction of the model if we are to trust it. We demand further that the predictions of the model be credible compared to other estimates of high-grading. When all prices are equal and the quota is free, there are no incentives to high-grade. We can therefore use the model to predict catch composition at equal prices and thereafter estimate the discards of each grade. Let be $\overline{\mathbf{p}}$ the vector of equal prices and let $\mathbf{w}^0$ be the zero price of quota. In the absence of incentives, equations (1), (20) and (21) become as follows.

$$\begin{aligned} & d_i(\overline{\mathbf{p}},\mathbf{w}^0,\boldsymbol{\theta}) = 0 \\ & y_i^0 = y_i(\overline{\mathbf{p}},\mathbf{w}^0,\boldsymbol{\theta}) = a_i y(\overline{\mathbf{p}},\mathbf{w}^0,\boldsymbol{\theta}) = a_i y^0 \\ & \sum_i y_i^0 = \sum_i a_i y^0 = y^0 \sum_i a_i = y^0 \\ & \hat{a}_i^0 = \frac{y_i^0}{\sum_i y_i^0} = \frac{y_i^0}{y^0} \end{aligned} \tag{34}$$

Assume that there is another set of prices, denoted by the superscript ^{1}, for which discards occur. These prices may be the average prices. Given that there exists a grade k for which no discarding occurs ($d_k = 0$), it is now possible to estimate the actual but unknown catch by substituting the results from (34) into (1) and obtain the following.

$$
\begin{aligned}
&y_k^1 = \hat{a}_k^0 y^1 \\
&y_k\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right) = \hat{a}_k^0 y\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right) \\
&y\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right) = \frac{y_k\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right)}{\hat{a}_k^0}
\end{aligned} \tag{35}
$$

The results from equation (35) allow us to solve for the unknown discarding for the discarded fish grades.

$$
\begin{aligned}
&y_i^1 = \hat{a}_i^0 y^1(x) - d_i^1 \\
&y_i^1 = \hat{a}_i^0 \left(\frac{y_k^1}{\hat{a}_k^0}\right) - d_i^1 \\
&d_i^1 = y_i^1 - \hat{a}_i^0 \left(\frac{y_k^1}{\hat{a}_k^0}\right) \\
&d_i^1 = y_i\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right) - \hat{a}_i^0 \left(\frac{y_k\left(\mathbf{p}^1, \mathbf{w}^1, \boldsymbol{\theta}^1\right)}{\hat{a}_k^0}\right)
\end{aligned} \tag{36}
$$

The estimated discarded quantity is the difference between the observed landed quantity and the estimated catch, which is based on the landed quantity of a nondiscarded size category and estimated catch shares. I will assume that the largest and most valuable cod is never discarded. I follow Palsson, Einarsson and Bjornsson (2003) and Palsson, Schopka, and Einarsson. (2003) and report discarding as a percentage of landings, or as follows.

$$
\bar{D} = \frac{\sum_i d_i}{\sum_i y_i} = \frac{D}{\sum_i y_i} \tag{37}
$$

Empirical model

The profit function is approximated by a locally flexible functional form. The translog, generalized Leontief, and generalized McFadden functional forms are commonly used to approximate profit functions. I use the generalized McFadden profit function because the estimation of discards depends on the use of zero prices, which neither the translog nor generalized Leontief can deal with. The generalized McFadden profit function results in output supply functions that are linear functions of prices. I make some slight modifications to the general form. The legal framework for discarding has not changed over the period of our empirical analysis, and the effects of discarding cost are therefore not distinguishable from the constant term. Furthermore, although fishing gear can be assumed to be inflexible, there is an interaction between the fish stock and the gear that must be taken into account (Palsson, Schopka, and Einarsson 2003). I include three season dummies, denoted by z_s, to achieve this. Dividing all prices by one price imposes homogeneity. Assume that the input price, w, is used as the asymptotic good. The generalized McFadden approximation of the profit function in (22) is (Diewert and Wales 1987):

$$
\begin{aligned}
\boldsymbol{\Pi}\left(\mathbf{p}, \mathbf{z}_s\right) = {} & \alpha_0 + \sum_{i=1}^{n} \alpha_{0i} p_i + \alpha_{0ITQ} w_{ITQ} + \sum_{i=1}^{n} \sum_{s=1}^{3} \beta_{is} z_s p_i + \sum_{s=1}^{3} \beta_{ITQs} z_s w_{ITQ} \\
& + \frac{1}{2w}\left[\sum_{i=1}^{n}\sum_{j=1}^{n} \gamma_{ij} p_i p_j + \sum_{i=1}^{n} \gamma_{ITQi} w_{ITQ} p_i + \gamma_{ITQITQ} w_{ITQ}^2\right]
\end{aligned} \tag{38}
$$

where $\mathbf{p}$ is the vector of prices, $\mathbf{z}$ is the vector of dummy variables, and α, β and γ are parameters. The symmetry restrictions implies that $\gamma_{mn} = \gamma_{nm}$, where m and n refer to both input and prices.

The output supply and input demand are derived by Hotellings lemma. For an output quantity, y_k, the output supply is as follows.

$$\frac{\partial \boldsymbol{\Pi}(\mathbf{p},\mathbf{w},\boldsymbol{\theta})}{\partial p_i} = y_i^* = \alpha_{0k} + \sum_{s=1}^{S} \beta_{sk}\mathbf{z}_s + \frac{1}{w}\left[\sum_{j=1}^{n} \gamma_{kj} p_j + \gamma_{kITQ} w_{ITQ}\right] \tag{39}$$

For the quota, x_{ITQ}, the input demand is as follows.

$$\frac{\partial \boldsymbol{\Pi}(\mathbf{p},\mathbf{w},\boldsymbol{\theta})}{\partial w_{ITQ}} = -x_{ITQ}^* = \alpha_{0ITQ} + \sum_{s=1}^{S} \beta_{sITQ}\mathbf{z}_s + \frac{1}{w}\left[\sum_{j=1}^{n} \gamma_{ITQj} p_j + \gamma_{ITQITQ} w_{ITQ}\right] \tag{40}$$

As all the equations in the model are linear in the parameters, the model is easily estimated using Zellner's iterative seemingly unrelated regression method, and using the LSQ procedure in TSP.

The elasticities at mean values from generalized McFadden output supply and input demand functions have the following form:

$$\varepsilon_{ij} = \frac{\gamma_{ij}}{\overline{w}} \frac{\overline{p}_j}{\overline{q}_i} \tag{41}$$

where $\overline{w}$, $\overline{p}$ and $\overline{q}$ are average values of the variables. The elasticity for the asymptotic good is calculated as follows.

$$\varepsilon_{in} = -\sum_{j=1}^{n-1} \varepsilon_{ij} \tag{42}$$

Data

Íslandsmarkaður, the Network of Icelandic fish auctions, provided the price and quantity data. They include the results of the daily auction data for cod over the period for which quota prices were available, September 1st 1998 to May 31st 2001. The registration of the fish sold in the auctions is very thorough, which makes it possible to differentiate by, for example, species, fishing method and size grade. About a third of the annual catch of cod is sold at the auctions. There are five methods predominantly used in the Icelandic cod fishery: trawl, Danish seine, long line, hand line and net. The cod sold at the auctions is mostly caught by one of the three last methods. However, as the hand-line vessels are small and many are not quota regulated, the theoretical model is not expected to apply to them. I will therefore focus on the long-line and net vessels in the empirical estimation. The auctions register a number of factors that potentially affect price. Three size classes are used in this analysis: small (<2.0 kg), medium (2.0–3.5 kg) and large (>3.5 kg). The price is defined as the average weekly price of all cod caught by a particular gear type and belonging to a particular grade. Weekly data were used to eliminate the substantial number of missing values generated on days where no fish of a particular grade was sold. The final dataset covers 141 weeks and is based on 116,159 individual transactions with a total quantity of 77 thousand tonnes and a value of 10.5 billion ISK or US$140 million ($1≈75 ISK).

The fishers deliver their catch to the fish auctions prior to the actual auction. Prices are therefore unknown to the fishers while they are fishing. It is natural to assume that the fishers are rational and that they make purposeful and efficient use of relevant information in optimizing their decisions. I assume therefore that the fishers have quasi-rational price expectations (Nerlove and Bessler 2001). This amounts to forming expectations of future prices with a best-fitting time series model. I apply a best fitting ARIMA model to each price, estimated with all available historical data from the auctions over the period January 1995 through August 1998. Stationarity is tested by a Dickey–Fuller test with a lag length chosen by the method described by Pantula, Gonsales-Farias and Fuller (1994). The Extended Sample Autocorrelation Function (ESACF) method of Tsay and Tiao (1984) is used to identify the orders of the ARMA process. The orders of the ARIMA models are shown in Table 1. The model was reestimated for each one-week-ahead prediction.

The quota price data are from the Directorate of Fisheries, which is an Icelandic Government institution responsible for implementing government policy on fisheries management and handling of seafood products. The Directorate enforces laws and regulations regarding fisheries management, monitoring of fishing activities and imposition of penalties for illegal catches. The data are from the central quota market, which existed from September 1st 1998 though May 2001. All quota transactions between companies had to go through the market, and other trades had to use the prices from the market. These prices will therefore accurately describe the quota cost or opportunity cost if own quota is used.

As this is a short-run model, there are few input factors that are truly variable. Capital is fixed on a week-to-week basis. The number of fishers on each boat is also fixed in the short run because of Icelandic labor regulations. Furthermore, the fishers are usually paid catch value shares, which means that labor cost is a function of output value. In essence, the only major input factor that the fisher can control is fuel oil. The price of oil for fishing vessels was provided by the oil retailer Oliufelagid ESSO, the largest provider of fuel and oil-based products to the Icelandic business sector.

Table 1. Descriptive statistics for all quantity and price variables in the model.

Vessel type	Good type	Variable type	Variable name[1]	Mean	Standard deviation	Min	Max	ARIMA model
Long-line	Small cod	Exp. Price[2]	p_1^{l-l}	105.7	59.3	84.7	122.9	1,0,1
Long-line	Medium cod	Exp. price	p_2^{l-l}	124.9	102.6	104.6	149.2	0,1,1
Long-line	Large cod	Exp. price	p_3^{l-l}	151.2	320.4	122.6	188.7	2,1,1
Net	Small cod	Exp. price	p_1^n	106.1	49.9	87.6	122.4	1,0,3
Net	Medium cod	Exp. price	p_2^n	124.9	102.3	104.7	149.1	0,1,1
Net	Large cod	Exp. price	p_3^n	151.1	318.2	123.5	189	0,1,1
Both	Quota	Price	w_{ITQ}	104.8	74.4	85.2	126	
Both	Oil	Price	w	19.7	37.2	12.3	30.6	
Long-line	Small cod	Quantity	y_1^{l-l}	36.1	23.6	2.8	120.9	
Long-line	Medium cod	Quantity	y_2^{l-l}	210.7	146.8	24	707.8	
Long-line	Large cod	Quantity	y_3^{l-l}	68.6	63.7	5	380.1	
Long-line	Quota	Quantity	x_{ITQ}^{l-l}	264.6	182.8	43.1	962	
Net	Small cod	Quantity	y_1^n	2.8	4.3	0	22.3	
Net	Medium cod	Quantity	y_2^n	43	50.2	0.3	302.5	
Net	Large cod	Quantity	y_3^n	188.1	202.4	3	1130.4	
Net	Quota	Quantity	x_{ITQ}^n	224.7	236.6	8.9	1287	

[1] Superscript in variable names refers to vessel type and subscript to good type.
[2] Price as predicted by the ARIMA model defined in the last column.
Prices are reported in ISK per kg and quantities in tonnes per week.

The average prices in Table 1 show that price increases with size grade. There are only small differences between the prices of cod from the long-line vessels and from the net vessels. Notice that the price of the smallest cod is only slightly above the quota price, indicating a real incentive to avoid it. The quantity composition of the landings from the two vessel types is very different. While long-line vessels mostly land medium-sized cod with a substantial amount of small cod in the mix, the net vessels primarily land large cod and some medium-sized cod but virtually no small cod. This underlines the importance of differentiating the estimation by vessel type.

Three seasonal dummy variables are added to the estimated model. The first covers the net season, which also is the second half of the long-line season, from February through April; the second covers the first half of the long-line season, November through January; and the third covers the first low season, May plus August, September and October. The constant term covers the lowest season, June and July. This definition approximates the reported landings of each vessel type by months as reported by, for example, Helgason (1996).

Empirical results

Only the elasticity estimates are reported as they are easier to interpret than the parameters of the generalized McFadden output supply and input demand functions. The estimated parameters are available from the author upon request. The estimated elasticities at mean from the net and line fishing models are reported in Tables 2 and 3 along with adjusted R^2.

Table 2. Estimated elasticities at mean of prices and quantities and adjusted R^2 for the net fishing model with *t*-values in parentheses.

			j=			
	1	2	3	ITQ	Oil	Adjusted R^2
ε_{1j}	3.39	2.40	-7.00	-0.75	1.96	0.41
	(2.76)	(0.95)	(2.83)	(0.74)	(3.45)	
ε_{2j}	0.13	1.94	-3.26	0.58	0.61	0.35
	(0.95)	(1.46)	(2.21)	(0.90)	(1.73)	
ε_{3j}	-0.07	-0.62	1.24	-0.30	-0.24	0.51
	(2.83)	(2.21)	(2.13)	(0.70)	(1.29)	
$\varepsilon_{\mathrm{ITQ}j}$	0.01	-0.13	0.35	-0.20	-0.03	0.50
	(0.74)	(0.90)	(0.70)	(0.47)	(0.18)	

The numbers refer to the definitions in Table 1.

All the own price supply elasticities are positive, and the input demand elasticity for quota is negative, as expected. The results show further that small and medium-sized cod are complements, while large cod is a substitute for small and medium-sized cod. This is not consistent with the no-high-grading hypothesis, which indicates that all size classes are complements. The quota elasticities are all negative, as expected. The oil price elasticity is significantly positive for the smallest cod but significantly negative for the largest cod. This is consistent with high-grading given a binding hold constraint, as it indicates that a higher oil price shifts the supply from large to small cod and reduces discarding.

Table 3. Estimated elasticities at mean of prices and quantities and adjusted R^2 for the long-line fishing model with *t*-values in parentheses.

			j=			
	1	2	3	ITQ	Oil	Adjusted R^2
ε_{1j}	1.53	-2.28	1.64	-1.06	0.17	0.38
	(2.39)	(2.52)	(2.09)	(2.96)	(0.92)	
ε_{2j}	-0.33	0.92	0.26	-0.50	-0.34	0.33
	(2.52)	(2.34)	(0.90)	(1.77)	(2.46)	
ε_{3j}	0.62	0.66	-0.68	-0.41	-0.18	0.31
	(2.09)	(0.90)	(0.94)	(1.01)	(0.81)	
$\varepsilon_{\mathrm{ITQ}j}$	0.15	0.48	0.15	-0.50	-0.27	0.35
	(2.96)	(1.77)	(1.01)	(1.82)	(2.10)	

The numbers refer to the definitions in Table 1.

The elasticity estimates for the long-line vessels, as reported in Table 3, are quite different than for net vessels. Only two own price elasticities are significantly different form zero, for small and medium-sized cod. Both have expected positive signs. The significant cross-price supply elasticities are all positive, which is consistent with the no-high-grading hypothesis. Furthermore, there is no clear evidence of different oil price elasticities for the supply of different grades. The overall impression is that the results are more consistent with there being no high-grading.

The results from the no-high-grading test, as described in equation (31), and the estimated discard rates of the small and medium-sized cod, described in equations (34) to (37), are reported in Table 4.

Table 4. Test results for the no-high-grading hypothesis and estimation results for the total quantity discarded at average prices as a percentage of landings for each discarded grade and total.

	P-value for the no high-grading hypothesis	Estimated discard rate Small	Medium	Total	Discards IMRI 2001[1]
Net	0.000	3.90%	0.79%	4.70%	3.00%
Long-line	0.008	2.44%	0.27%	2.71%	1.00%

[1] Estimates reported by the Icelandic Marine Research Institute in Palsson, Schopka, and Einarsson (2003)

The results in Table 4 clearly indicate that the null no-high-grading hypothesis is rejected for both vessel types. Although the null hypothesis is clearly rejected, the discarded amount is small. The estimates of discards are consistent with the theoretical model that predicts that the small cod is discarded and that only a small amount of the medium-sized cod is discarded. The discard rates are close to the estimates reported by the Icelandic Marine Research Institute (IMRI) (Palsson, Schopka, and Einarsson 2003), which bases its estimates on comparing the length distribution of landings and catch samples in 2001. The discard rates are consistent with the elasticity estimates and clearly suggest that discarding is more common in the net fisheries than in the long-line fisheries. The difference between the two fishing methods is further exaggerated if we look at the average landings reported in Table 1. Only about 1% of average landings of net vessels are small cod, compared with 11% for long-line vessels. According to this, only one or two out of 10 small cod that are caught are discarded by the long-line vessels, while as many as seven or eight out of 10 are discarded by the net vessels. Although both solutions are internal, the solution for the net vessels looks much more like a corner solution where all the small cod are discarded. Nevertheless, the discard ratios are small, and the results seem to verify the results of the IMRI; i.e., that discarding is not a substantial problem in the Icelandic cod fisheries and is less so for long-line vessels than for net vessels.

The theoretical model predicts that the effects of quota price and oil price on high-grading depend on whether the hold constraint is binding. If the hold constraint is not binding, then the oil price does not affect discarding. On the other hand, if the hold constraint is binding, then quota price does not affect discarding. Table 5 presents the test results of the no-quota-price-effect and no-oil-price-effect hypotheses.

Table 5. Test of the no-quota-price-effect and no-oil-price-effect null hypotheses on discarding.

	H_0: No quota price effect P-value	H_0: No oil price effect P-value
Net	0.041	0.001
Long-line	0.336	0.040

According to the results in Table 5, the no-quota-price-effect hypothesis is only rejected for the net fishing vessels, while the no-oil-price-effect hypothesis is rejected for both vessel types. The results for the net vessels indicate that the hold constraint is only sometimes binding and then quota-induced discarding occurs. On the other hand, only oil prices significantly affect the discarding on the long-line vessels. This may indicate that the more even supply pattern of long-line vessels, as seen in the descriptive statistics in Table 1, results in higher capacity use and less quota-induced discarding.

Conclusions

The theoretical model of high-grading behavior by fishers shows that ITQs may provide incentives for high-grading but only as long as there is free hold capacity. Progressive punishments and monitoring schemes effectively reduce the quantity discarded. If hold capacity is binding, then the quota price does not induce discarding.

The results of the empirical estimation indicate that high-grading occurs in the Icelandic cod fishery on both long-line and net vessels. However, the discarding rates are small, and the results clearly suggest that ITQ-induced high-grading can effectively be dealt with by a ban on discards, as has been done in Iceland. This method should therefore be considered as a supplement in ITQ-regulated fisheries as a cost-effective way of reducing the high-grading incentives incorporated in the system.

The estimated discard rates are consistent with existing estimates for the same types of vessel in the same fishery. This suggests that the method is an accurate and useful alternative to existing methods for estimating discards. The availability of the type of data used in this study is increasing as more fish markets employ electronic sales systems. The cost of estimation associated with this method is small, and it can be performed routinely by statistical agencies to help resource managers choose the level of monitoring in response to changes in estimated high-grading, thus increasing the effectiveness of monitoring.

Discard rates are considerably larger for the net vessels than for the long-line vessels. The results suggest that the net vessels discard most of the smallest cod. Tests of which input prices affect discarding identifies the oil price for both vessel types, but the quota price only for net vessels. This may be taken to suggest that the lower discard rates of the long-line vessels are partly due to better capacity use and therefore fewer quota-induced discards. The results indicate that resource managers should focus monitoring attention on net fishing vessels rather than long-line vessels, or more generally on highly seasonal fisheries where hold capacity is only limited for short periods.

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Endnotes

[i] Note that this test relies heavily on the assumptions about technology. If these assumptions do not hold, then it will become a joint test of output flexibility and no discarding.

[ii] Note that the interpretation simulation results rely on the assumptions about technology. If the assumptions do not hold and there is some output flexibility, then the results will estimate the upper level of discards rather actual discards.