Marine Resource Economics, Volume 9, pp. 189–207
0738-1360/94 $3.00 + .00

On Catch Discarding in Fisheries

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Abstract *This paper examines the economics of catch discarding in fisheries. To study this issue a simple dynamic fisheries model is constructed. On the basis of this model it is demonstrated that in a differentiated fishery discarding of catch may be socially optimal. The paper goes on to show that individual firms in a free access, competitive fishery employ the socially optimal discarding rule. In contrast, the individual transferable quota (ITQ) fisheries management regime tends to generate an excessive incentive for discarding catch. The problem, however, does not appear to derive from the ITQ system as such. Rather, it seems to depend on the imperfect application of the system to real fisheries. The concept of a discarding function is defined and it is shown that at least within the framework of the model employed the discarding function for an ITQ fishery dominates the one for free access, competitive fisheries. Numerical examples are provided. Finally, possible remedies of the discarding problem are briefly discussed.*

Keywords Fisheries economics, ITQs, discarding, highgrading, discarding function, differentiated fishery.

Introduction

A fundamental axiom of economics states that economic agents strive to maximize their objective functions subject to the constraints under which they operate. This axiom is of course supposed to apply to fishing firms no less than other economic entities. This suggests that the principal goal of fisheries management theory should be to identify an institutional (or regulatory) framework with the property that the efforts of individual fishing firms to improve their fortunes result in the maximization of the common good.

Many fisheries management frameworks induce behaviour that, while individually profit maximizing, is collectively suboptimal in the sense of being Pareto inferior. The prime example of this is the free access, common property fisheries management system.[1] More generally, it is important to recognize that all fisheries management regimes, even those specifically designed to alleviate the common property problem, are subject to the above-mentioned fundamental axiom of economics. Irrespective of the particular fisheries management regime adopted, fishermen are constantly seeking ways to increase their individual returns within (and

* An earlier version of this paper was presented at the International Conference on Fisheries Economics in Bergen 1993. I am grateful to the participants of this conference for helpful comments. The paper was further improved by constructive comments by two anonymous referees.

[1] The basic reference here is Gordon (1954). For a more modern analysis see Clark and Munro (1982).

sometimes without) that particular management framework. Under an ideal fisheries management regime (which may not exist) these efforts only serve to maintain and further the objectives of management. In less favourable cases, these efforts tend to subvert the intended effects of the fisheries management. In extreme cases attempts by individual players to improve their individual lot will completely frustrate the objectives of the fisheries management.[2]

The individual transferable quota system (ITQ) appears to be one of the most promising fisheries management system to alleviate the common property problem and to improve the efficiency of ocean fisheries.[3] Economists have long suspected that this system encourages excessive discarding of catch. Thus Rettig (1986) regards the possibility of increased discards as a great concern with ITQ programs.[4] The issue is further explored in Squires and Kirkley (1991) and in greater detail in Anderson *et al.* (1992).[5] None of these references, however, present a formal analysis of the issue.

In Iceland where a comprehensive individual transferable share quota system (ITSQ) has been in effect for some years, opponents of the system sometimes assert that the system generates a great deal of waste through discarding of catch. Measurements of discarding in the Icelandic multispecies demersal fisheries have not produced much evidence in support of this assertion. Thus a recently published study[6] found no discernible increase in discards under the ITSQ system compared to the previous limited effort fisheries management system. Under both systems discards ranged from 1–6% of total catch volume depending on gear and vessel type.

Casual empiricism as well as economic intuition suggests that discarding of catch may take place under most fisheries management systems. In fact, some discarding may actually be economically optimal. This suggests that research into the discarding issue should focus on the possible existence of excessive incentives for discarding associated with different management regimes, the magnitudes involved and possible remedies.

This paper deals with these questions. In particular, it attempts to investigate whether there is an increased tendency toward discarding in an ITQ fisheries management system compared to the free access alternative and to identify the factors responsible. The paper proceeds to present numerical examples to throw light on the potential magnitude of the problem. Finally, possible remedies of the problem are briefly discussed.

Basic Model

The analysis of discarding requires a model slightly more detailed than the standard, aggregative fisheries model.[7] Discarding, as will be shown below, only

[2] Examples are provided by attempts to increase economic rents in fisheries by total quota management regimes and effort restrictions. See e.g. Scott and Neher (1981), Arnason (1986) and Hannesson (1993).
[3] See e.g. Arnason (1990).
[4] See also Rettig (1989).
[5] See also the other volumes of the National ITQ Study Report, NOAA (1992).
[6] See Nefnd um Motun Sjavarutvegsstefnu (1993).
[7] As expressed for instance in such classic texts as Gordon (1954) and Clark and Munro (1982).

makes economic sense in what may be referred to as the *differentiated fishery*. This is a fishery that is characterized by more than one economic grade of the catch.

Any volume of catch hauled aboard a fishing vessel may be composed of a number of economic grades. Typically these grades reflect different landing prices of individual fish, different handling costs aboard the vessel etc. To be relevant for discarding, the grades must be detectable by the fishermen. This means that the relevant grades are normally associated with physical appearance of individual fish such as its size, skin damage, colour etc.

Let the index i refer to economic grades in the catch. Clearly the number of grades relevant for discarding is at most equal to the number of individual fish in the catch. Let this number be I and refer to catch of grade i as $y(i)$, $i = 1, 2, \ldots I$. Aggregation of catch over grades yields total catch as $y \equiv \Sigma_i y(i)$, where the summation is over all grades $i = [1, I]$. To the extent that different grades of catch derive from features of the biomass, we correspondingly have $x(i)$ representing biomass of grade i. In order to focus on the essential aspects of discarding, however, the analysis will proceed in terms of aggregate biomass defined by $x \equiv \Sigma_i x(i)$.

Let instantaneous harvesting be determined by the following strictly increasing, jointly concave harvesting function:

$$y \equiv \Sigma_i y(i) = \Sigma_i Y(e,x,i), \text{ for all } i \text{ and } e,x \geqslant 0,\ Y(0,x,i) = Y(e,0,i) = 0 \quad (1)$$

where $y(i)$, as mentioned, denotes harvesting of fish of grade i and x the aggregate biomass. The variable e represents fishing effort. This is assumed to be undifferentiated by grades. All variables are functions of time.

It is worth noting that the harvesting functions in (1) constitute examples of joint production functions. The economic input, e, cannot be differentiated according to grades. Therefore, the vessel will have to harvest whatever grade composition of catch that is produced by e given the aggregate biomass, x.[8]

Aggregate biomass develops according to the usual rule in aggregate fisheries models:

$$\dot{x} = G(x) - y, \text{ for } e,x \geqslant 0, \quad (2)$$

where the natural biomass growth function, $G(x)$, is assumed to have the usual shape with $G(0) = G(x_1) = G(x_2) = 0$ for $0 \leqslant x_1 < x_2$ and $G_{xx} < 0$.

Finally harvesting costs are given by the strictly increasing convex cost function:

$$CE(e), \text{ for } e \geqslant 0,\ CE(0) \geqslant 0. \quad (3)$$

Apart from disaggregation of catch into grades, expressions (1)–(3) are essen-

[8] The case where fishing effort can be differentiated according to fish grades at a cost is interesting. This can be modelled in a straight-forward manner by employing a $1 \times I$ vector of fishing efforts, *i.e.*, $\boldsymbol{e} = (e(1), e(2), \ldots, e(\mathrm{I}))$ and a corresponding vector of cost functions, $\boldsymbol{c} = (c(e(1)), c(e(2)), \ldots, c(e(\mathrm{I})))$. Again, however, in order to focus on the essential elements of the discarding issue this particular avenue is not pursued in this paper.

tially identical to the standard aggregate fisheries model.[9] Adding to this model the option of catch discarding we have the identity:

$$l(i) \equiv Y(e,x,i) - d(i), \tag{4}$$

where $Y(e,x,i)$ represents the harvest of grade i at time t as specified above, $l(i)$ retained or landed harvest and $d(i)$ the discarded harvest of grade i. A negative level of discarding would be harvesting. Therefore we assume that $d(i) \geqslant 0$, all i. Also, since fisheries are characterized by nonnegative landings, we impose the restriction $l(i) \geqslant 0$, all i, in this model.[10]

There would generally be economic costs associated with landings and discarding. Let us represent those by the nondecreasing, convex cost functions:

$$CL(l(i),i), \text{ for } l(i) \geqslant 0, \text{ all } i, \ CL(0) \geqslant 0, \tag{5}$$

$$CD(d(i),i), \text{ for } d(i) \geqslant 0, \text{ all } i, \ CD(0) \geqslant 0. \tag{6}$$

The $CL(\ )$ functions represent various costs associated with retaining catch of grade i and landing it. These costs include the cost of preliminary fish processing aboard the vessel; handling, gutting, storing, preserving etc., as well as the actual landing costs.

The $CD(\ )$ functions represent the costs associated with discarding of fish of grade i. As discarding is generally relatively easy, these costs would in most cases be small. Notice, however, that if discarding is illegal or socially frowned upon, discarding costs would tend to be correspondingly higher.

Given the specifications in (1) to (6) we may write the instantaneous profit function of the fishery as:

$$\pi(e,\boldsymbol{d};x;\boldsymbol{p}) = \Sigma_i p(i) \cdot l(i) - CE(e) - \Sigma_i CL(l(i),i)) - \Sigma_i CD(d(i),i), \tag{7}$$

where $p(i)$ denotes the price of one unit of landings. The $(1 \times I)$ vectors $\boldsymbol{d}$ and $\boldsymbol{p}$ represent discarding and quay prices of different grades of fish, respectively. In this profit function fishing effort, e, and discarding, $\boldsymbol{d}$, are natural control variables. Biomass, x, is a state variable and the fish prices, $p(i)$, are parameters.

Before proceeding, a few additional limitations of the model should be observed. First, note that (2) contains the implicit assumption that discarded catch does not revert to the biomass. In many fisheries, especially deep sea ones, this is empirically accurate. In others, *e.g.* some inshore crab and shellfish fisheries, a substantial fraction of the discarded catch survives and is, thus, not lost from the biomass. A more general formulation of equation (2) allowing for this possibility is:

$$\dot{x} = G(x) - y + \alpha \cdot \Sigma_i d(i), \ 1 \geqslant \alpha \geqslant 0, \tag{2'}$$

where α is a survival parameter.

[9] See *e.g.* Clark and Munro (1982).
[10] Negative landings, however, appear to have an interesting interpretation e.g. in terms of ocean ranching and waste disposal.

Second, the structure of the model presupposes that landings, harvesting and discarding may take place simultaneously, while in reality harvesting is more like a prolonged affair interspersed with landings. In a later section, this particular assumption is relaxed and the implications for discarding investigated.

Optimal Discarding

The social problem is to adjust fishing effort and the vector of discards so as to maximize present value of profits from the fishery. More precisely:

$$\underset{e,\mathbf{d}}{\text{Max}} \int_0^\infty \pi(e,\boldsymbol{d},x;\boldsymbol{p}) \cdot exp(-rt)dt \tag{I}$$

$$\text{Subject to: } \dot{x} = G(x) - \Sigma_i y(i),$$
$$e,\boldsymbol{d} \geq 0,$$

where r denotes the rate of discount. As before, e and x represent fishing effort and biomass respectively and $\boldsymbol{d}$ and $\boldsymbol{p}$ $(1 \times I)$ vectors of discarding and prices corresponding to different grades. The functions y, $G(\cdot)$ and π are defined in equations (1), (2) and (7) above.

Among the necessary conditions for solving problem (I) are:

$$\begin{aligned} \pi_e - \mu \cdot \Sigma_i Y_e \equiv \Sigma_i(p(i) - CL_l) \cdot Y_e - CE_e - \mu \cdot \Sigma_i Y_e \leq 0, \\ e \geq 0,\ e \cdot (\pi_e - \mu \cdot \Sigma_i Y_e) = 0, \end{aligned} \tag{I.1}$$

$$\pi_{d(i)} \equiv -p(i) + CL_l(l(i)) - CD_d(d(i)) \leq 0,\ d(i) \geq 0,\ d(i) \cdot \pi_d(i) = 0, \text{ all i} \tag{I.2}$$

where μ is the so-called costate variable or imputed (shadow) value of biomass.

Condition (I.1) is the usual fishing effort efficiency condition in fisheries models. Thus, (I.1) requires that for positive fishing effort instantaneous marginal profits of effort, taking full account of the value of fish in the sea, should be zero.

Condition (I.2) gives the rule for socially optimal discarding of catch. In a slightly more convenient form the discarding rule is:

$$d(i) > 0 \text{ if } p(i) + CD_d(0,i) < CL_l(Y(e,x,i) - 0,i) \tag{8}$$

The left-hand-side of the second inequality of the discarding rule, namely $p(i) + CD_d(0,i)$, represents the marginal costs of discarding. This cost consists of two parts; the unit price of landed catch foregone by discarding, $p(i)$, and the direct marginal costs of discarding evaluated at zero discarding, *i.e.*, $CD_d(0)$. The right-hand-side of (8), $CL_l(Y(e,x,i) - 0,i)$, represents the marginal benefits of discarding (or marginal costs of retaining) catch also evaluated at zero discarding. Thus, the discarding rule expressed in (8) is very simple. Catch of grade i should be discarded, *i.e.*, $d(i) > 0$, if the marginal benefits of discarding exceed the costs.

There is a couple of things to notice about the discarding rule. First, since fishing effort and biomass, *i.e.*, e and x, appear in the discarding rule and the vector of discarding, $\boldsymbol{d}$, appears in (I.1), it is clear that the optimal levels of the two control variables, e and $\boldsymbol{d}$, are in general interdependent. This means that the optimal level of fishing effort depends on the discarding vector and vice versa.

Second, the discarding rule does not involve μ, the shadow value of biomass. The reason is that, under the current specifications, discarding does not affect the biomass in any way. Thus, while biomass influences the decision to discard via the harvesting function, there is no reciprocal impact. In this sense the stock dynamics of the problem are exogenous to the discarding rule.

It follows that the decision to discard is essentially static. This, of course, significantly simplifies the analysis. It is important to realize, however, that this property is solely due to our specification of the model and does not constitute a general feature of the discarding problem. As discussed in the previous section, the model specifications contain the implicit assumption that once a unit of biomass has been harvested it cannot be restored by discarding. Thus, discarding has no effect on biomass. If the reverse were true, *i.e.* equation (2) was replaced by equation (2′) the shadow value of biomass would appear in the discarding rule, encouraging discarding and complicating the analysis.

Let us for convenience refer to the expression

$$\Gamma(i) = CL_l(y(i) - 0,i) - p(i) - CD_d(0,i) \tag{9}$$

as the *discarding function* for grade i. If the discarding function for a particular grade is positive, marginal catch of that grade is discarded. If $\Gamma(i)$ is negative, catch of grade i is retained. Notice that the discarding function is not equivalent to the quantity discarded. It may, on the other hand, be interpreted as the tendency to discard.

The discarding function shows that the optimal decision to discard depends directly on (a) the quay price, (b) the marginal landing costs and (c) the marginal discarding costs of the grade in question. It seems empirically likely that $CL_l(y(i) - 0)$ is increasing in the catch rate, $y(i)$, at least for $y(i)$ above a certain level. In that case, the discarding function implies that the tendency to discard increases with the catch rate. This, in fact, appears economically plausible. Moreover, as catch increases monotonically with biomass and fishing effort, the tendency to discard also generally increases with these variables, *ceteris paribus*. On the other hand, the tendency to discard a particular grade diminishes with the price of catch, $p(i)$, and the marginal cost of discarding, $CD_d(0)$. This also appears economically plausible.

In an attempt to provide a partial visual image of the discarding function its dependence on the price of catch is illustrated in Figure 1.

The discarding function as a function of grades is more interesting. This function may in principle have any shape. One example is illustrated in Figure 2. For concreteness, the grades in Figure 2 may be thought of as fish size. The discarding function drawn suggests discarding at small and large sizes with catch being retained for middle sized fish.

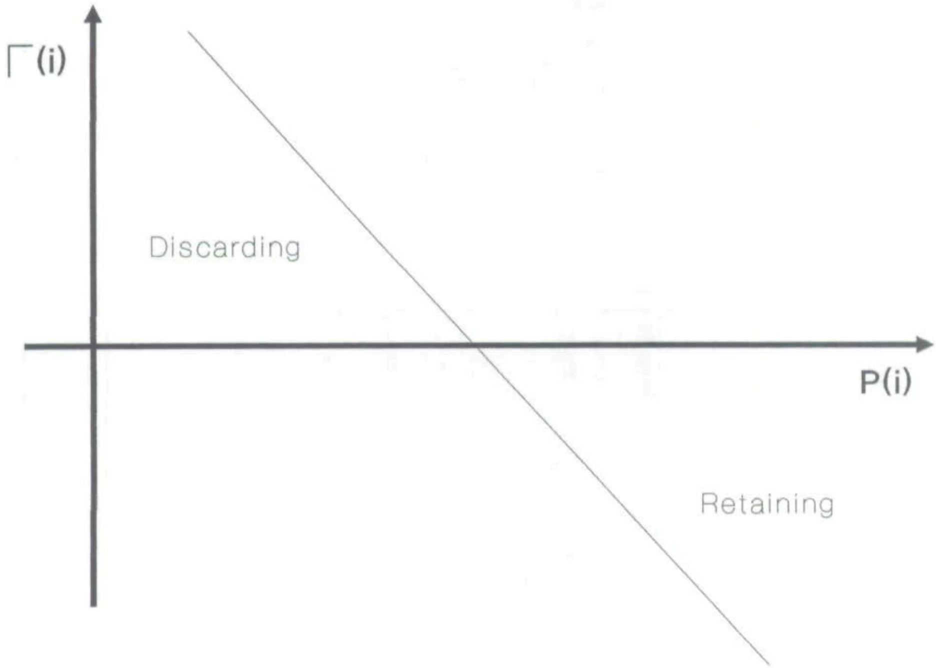

Figure 1. The discarding function: The effect of price.

The analysis so far suggests three seemingly interesting propositions concerning optimal discarding:

Proposition 1

In an undifferentiated fishery discarding of catch is not optimal.

Proof:

In an undifferentiated fishery the number of catch grates is unity, $I = 1$. Assume that $d(1) > 0$. Then, according to (I.2), $p(1) - CL_l(1) = -CD_d(1)$. Substituting this into (I.1) yields $-(CD_d(1) + \mu) \cdot Y_e(1) - C_e \leqslant 0$. But the right hand side is actually strictly negative because profit maximization requires $\mu \geqslant 0$. Consequently, by (I.1) $e = 0$. Thus, there is no catch to discard and $d(1) = 0$.[12] This contradiction proves the proposition.

Proposition 2

Discarding of catch may be socially optimal.

Proof:

This is immediate. For $I \geqslant 2$ it is clearly possible to select $p(1)$, $p(2)$, such that $e > 0$ and $\Gamma(2) > 0$ for given x, $CL_l(y(i) - 0,i)$ and $CD_d(0,i)$.

[12] It may be noted, however, that discarding might be positive if $CD_d < 0$, i.e. the act of discarding is economically beneficial.

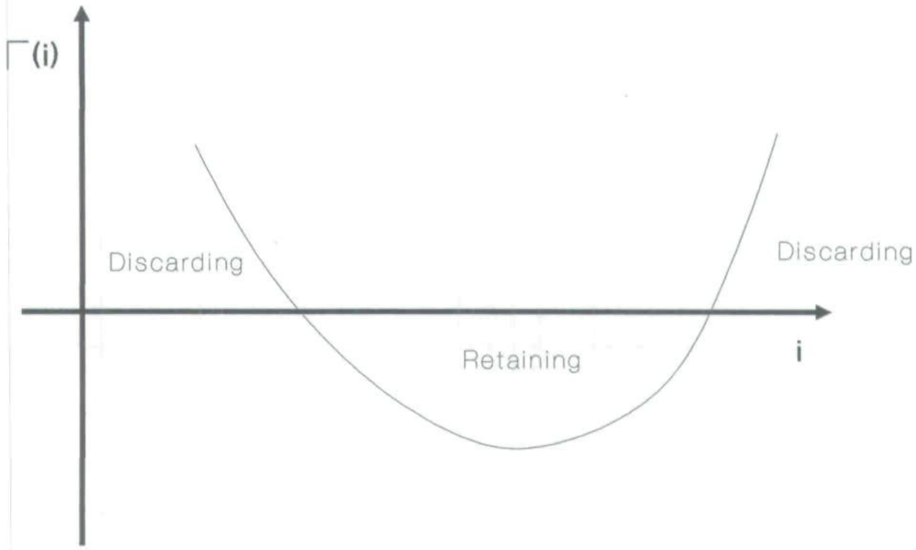

Figure 2. A discarding function.

Proposition 3

In a differentiated fishery no discarding may be optimal.

Proof:

Again, this proof is immediate. For a given number of grades, I, x, $CL_l(y(i) - 0,i)$ and $CD_d(0,i)$ simply increase all $p(i)$ until $\Gamma(i) < 0$ for all i.

Free Access, Competitive Fisheries

Let us now briefly consider discarding in a free access, competitive fishery. Under this fisheries regime an arbitrary firm, j, will attempt to solve the following problem:

$$\underset{e(j),\boldsymbol{d}(j)}{\text{Max}} \int_0^\infty \pi(e(j),\boldsymbol{d}(j),x;\boldsymbol{p}) \cdot exp(-rt)dt \tag{II}$$

$$\text{Subject to: } \dot{x} = G(x) - \Sigma_k \Sigma_i Y(e,x,i),$$
$$e(j),\boldsymbol{d}(j) \geqslant 0,$$

where as before r denotes the rate of discount, $e(j)$ firm j's fishing effort, and x biomass. $\boldsymbol{p}$ are $(1 \times I)$ vectors of discarding and prices, respectively, corresponding to different catch grades. $\pi(e(j),\boldsymbol{d}(j),x;\boldsymbol{p})$ represents firm j's profit function corresponding to equation (7) above. The summation, Σ_k, is over all firms in the industry.

A solution to this problem includes the discarding rule:

$$d(i,j) > 0 \quad \text{if} \quad p(i) + CD_d(0,i,j) < CL_l(Y(e(j),x,i,j) - 0,i,j), \text{ all } i, \tag{10}$$

where $d(i,j)$ is firm j's discarding of catch of grade i.

Comparing the competitive discarding rule, (10), with the socially optimal one, (8) in the previous section shows that the two are formally identical. In fact, formulating the social problem in terms of the same number of fishing firms yields the same discarding rule.

This result is not difficult to understand. Competitive utilization of fish stocks deviates only from the optimal one due to the stock externality. The discarding activity, at least as formulated here, does not generate any external effects.[13] Hence, competitive profit maximizing discarding rule should be optimal. It is important to realize, however, that this does not mean that the level of competitive discarding is socially optimal. Competitive discarding is only socially optimal conditional upon the existing competitive catch and biomass levels. These, however, are generally sub-optimal as is well known.

Individual Transferable Quotas

We will now turn our attention to catch discarding under ITQ fisheries management systems. We will first analyse the issue within the theoretically more convenient continuous ITQ system and then briefly consider discarding under a discontinuous ITQ system.

A Continuous ITQ System

Consider a continuous individual transferable quota (ITQ) system of the type specified by Arnason (1990). The essentials of this system are as follows: The fishing firms hold a stock of permanent ITQs. These ITQs refer to aggregate catch volumes and are not differentiated according to grades. Let $q(j)$ denote firm j's quota holding by firm j at time t. At each point of time quota holdings must at least equal the firm's rate of catch. However, if discards are not counted against quota, as is in fact generally the case, firm's j instantaneous quota constraint is:

$$q(j) \geqslant \Sigma_i l(i,j) \equiv \Sigma_i [y(i,j) - d(i,j)], \tag{11}$$

where $l(i,j)$ denotes the instantaneous landings of catch of grade i by firm j, $y(i,j)$ the instantaneous catch and $d(i,j)$ the corresponding discard.

Quota holdings can be adjusted by trading, z, at a market price, s. Thus, quota holdings move over time according to the equation:

$$\dot{q} = z. \tag{12}$$

Now, under quite unrestrictive assumptions, in particular that the quota price is positive,[14] the total quota (TAC) determined by the quota authority equals total landings. The actual development of biomass, however, depends on natural growth and total catches including discards. I.e.,

$$\dot{x} = G(x) - \mathrm{Q} - \Sigma_j \Sigma_i d(i,j), \tag{13}$$

[13] Discarding would, however, produce an externality (presumably a positive one) if some fraction of discarded catch survived and thus constituted additions to the biomass.
[14] See Arnason (1990).

where Q represents the total quota issued and, as before, Σ_j denotes summation over all firms in the fishery.

Within this management framework fishing firm j attempts to solve the following problem:

$$\underset{e(j),z(j),\boldsymbol{d}(j)}{\text{Max}} \quad V = \int_0^\infty [\pi(e(j),\boldsymbol{d}(j),x;\boldsymbol{p}) - s \cdot z] \cdot exp(-rt)dt \tag{III}$$

$$\begin{aligned} \text{Subject to: } \dot{q} &= z, \\ \dot{x} &= G(x) - \text{Q} - \Sigma_j\Sigma_i d(i,j), \\ q &\geqslant \Sigma_i[Y(e,x,i) - d(i)] \equiv \Sigma_i l(i,j), \\ e(\text{j}),&\boldsymbol{d}(\text{j}) \geqslant 0, \end{aligned}$$

where the instantaneous operating profit function for firm j, $\pi(e(j),\boldsymbol{d}(\text{j}),x;\boldsymbol{p})$, is as specified in (7) above.

It appears convenient to express a relevant current value Hamiltonian function for this problem as:

$$\begin{aligned} \text{H} = {} & \pi(e(\text{j}),\boldsymbol{d}(\text{j}),\boldsymbol{x};\boldsymbol{p}) - s \cdot z + \mu(j) \cdot z + \delta(j)(G(x) - \text{Q} - \Sigma_j\Sigma_i d(i,j)) \\ & + \sigma(j) \cdot (q - \Sigma_i l(i,j)), \end{aligned}$$

where $\mu(j)$ and $\delta(j)$ are costate variables or dynamic Lagrange multipliers corresponding to the state variables q and x, respectively and $\sigma(j)$ is the Lagrange multiplier associated with the quota constraint. Along the optimal path $\sigma(j)$ measures the instantaneous marginal profits of quota holdings to the firm.

A solution to problem (III) includes the discarding rule for firm j:

$$\begin{aligned} d(i,j) > 0 \quad \text{if} \quad & p(i) + CD_d(0,i,j) < CL_l(Y(e(j),x,i,j) - 0,i,j) \\ & + \sigma(j) - \delta(j), \text{ all } i. \end{aligned} \tag{14}$$

This discarding rule is similar to the socially optimal and competitive ones expressed in equations (8) and (10) above. The only formal difference is the inclusion of the two Lagrange multipliers, $\sigma(j)$ and $\delta(j)$, in (14).

The Lagrange multiplier, $\sigma(j)$, represents the instantaneous imputed shadow price or marginal value of quotas to firm j. Since quotas can be freely left unused, maximization of profits requires this term to be nonnegative.[15] Thus, landing of catch represents a cost to the firm amounting to $\sigma(j)$. Hence, $\sigma(j)$ normally encourages discarding of catch.

To provide another view on $\sigma(j)$ it may be remarked that $\sigma(j)$ equals the opportunity cost of holding a unit of quota. More precisely, it can be shown that $\sigma(j) = r \cdot s - \partial s/\partial t$. Now, s is the price of a permanent quota. Therefore, $r \cdot s$ represents the instantaneous interest foregone by holding a unit of quota, sometimes called quota rental. $\partial s/\partial t$ represents the capital gain (loss) of holding

[15] For the mathematical details consult the Kuhn-Tucker theorem, see e.g. Takayama (1974).

quota. In equilibrium $\sigma(j) = r \cdot s$, where, of course, $r \cdot s$ is the instantaneous or the rental price of quota. Thus, in equilibrium, $\sigma(j)$ is represents the instantaneous gain foregone by using the quota for landings instead of discarding the catch and renting the quota.

The other Lagrange multiplier, $\delta(j)$ represents firm j's shadow value of biomass. More precisely, $\delta(j) = \partial V(j)/\partial x$. The appearance of this multiplier in the discarding rule reflects the fact that in spite of the quota restriction, firm j can influence the path of the biomass via discarding of catch. Since higher biomass is normally economically beneficial to the firm,[16] $\delta(j)$ is usually positive. Hence, $\delta(j)$ represents a disincentive to discarding. $\delta(j)$, in other words, works against the quota price incentive to discard represented by $\sigma(j)$. In a fishery composed of many firms, however, $\delta(j)$ is comparatively small. More precisely, in equilibrium $\delta(j) = \alpha(j) \cdot \sigma(j)$, where $\alpha(j) \in [0,1]$ is firm j's share in the fishery.[17] Thus, for many practical purposes $\delta(j)$ is negligible and may be ignored.

Let us now for convenience refer to the quantity $\sigma(j) - \delta(j)$ as $\Omega(j)$. $\Omega(j) \equiv \sigma(j) - \delta(j)$, thus represents the deviation of the discarding rule under an ITQ system from the optimal one represented by (8) and (10). A positive $\Omega(j)$ represents an excessive incentive for discarding under an ITQ system and vice versa. In most commercial fisheries, $\Omega(j)$ would be expected to be nonnegative. As previously indicated, $\Omega(j)$ is closely related to the instantaneous quota price provided there is a reasonably large numbers of firms in the industry. In fact, in equilibrium, $\Omega(j)$ is approximately equal to the present value of this price.

The ITQ discarding function corresponding to (14) is:

$$\Gamma(i) = CL_l(y(i) - 0,i) + \Omega(j) - p(i) - CD_d(0,i). \tag{15}$$

Since $\Omega(j)$ is normally positive there is, for any given level of catch and price, $y(i)$ and $p(i)$, an added incentive for a profit maximizing firm i to discard catch under an ITQ system compared to what is socially optimal and a profit maximizing firm would elect to do under a competitive fisheries regime.[18] Alternatively we may say that the discarding function under an ITQ system, for given levels of $p(i)$ and $y(i)$ strictly dominates the socially optimal one.

We formalize this result as the following proposition:

Proposition 4

Under the ITQ system described above and when there is more than one fishing firm there is generally an excessive incentive for discarding catch.

The result expressed in Proposition 4 is economically quite intuitive. Under a competitive fisheries management regime, a fisherman contemplating whether or not to retain a particular fish will obviously elect do so if the net return (measured as the sum of its quay price and discarding costs less the landings costs) is positive. Under an ITQ system, this net return must be compared to the alternative benefits of discarding the fish and selling the corresponding quota. More precisely, the net return of landing the fish must exceed the quota price.

[16] $Y_x(e,x) > 0$.
[17] For arguments to this effect see Arnason (1990) pp. 634–5.
[18] As evidenced by equations (9) and (10).

Notice, however, that the result expressed in Proposition 4 does not necessarily mean that there will be excessive discarding under an ITQ system. There may be corner solutions. This means that if there is no discarding under a competitive fisheries management regime, there may possibly be no discarding under an ITQ system as well. On the other hand, if there is discarding under a competitive regime, there will almost certainly be excessive discarding under an ITQ system.

Why does the ITQ system that is designed to eliminate the common property problem in fisheries by allocating private property rights introduce a new inefficiency in the form of excessive catch discarding? The problem does not appear to be the ITQ system as such. The problem appears to derive from the imperfectness of the quota property rights as modelled in this paper or, alternatively, the enforcement of these rights.

To the extent that the quota restriction applies to landings rather than catch, the quota property rights are incomplete. Enforcing the quota restriction by monitoring landings is clearly a case of regulating the wrong target. Fishing firms can still impose stock externalities on each other by discarding catch. In that way they undermine the economic value of the quota property rights. The situation is not dissimilar to a property rights system on land where theft is illegal but vandalism is allowed.

To the extent that the ITQs refer to the aggregate volume of catch, the associated property rights are also incomplete in another respect. Different grades of catch represent economically different commodities. Quotas, on the other hand, are not differentiated by grades. Consequently, different grades of catch cannot correspond to different quota prices. This, of course, is the familiar problem of missing markets. The theoretical solution is to issue quotas by grades.[19] This, however, may not be practical.

Comparison of the discarding rules under the competitive and the ITQ regimes suggests that empirical inferences on the basis of observed differences in discarding are by no means straight-forward. Discarding depends *inter alia* on vessel catch rates and fish prices. Both of these may differ across the two management regimes. Compared to a competitive arrangement, an ITQ managed fishery may be expected to involve a higher catch rate per vessel. If the landings cost function, $CL(l)$, is convex, this induces a higher rate of discards under the ITQ fishery. This increase, by itself, is not, evidence of excessive discarding. On the contrary. It may, in fact, be socially optimal. Clearly, this observation has significant implications for the design of official campaigns to curtail discarding of catch.

A Discontinuous ITQ System

Most actual ITQ systems are not continuous. Continuous ITQ systems are simply not very practical. In most ITQ systems the quota restriction only constrains the integral of catches over a period of time. Moreover, the quota holdings are only adjusted for catch at the time of landing. This particular practice of ITQ systems slightly modifies but does not materially affect the results derived above. We will now briefly investigate this:

[19] This was in fact suggested by Helgason (1989).

Consider an ITQ system where the quota constraint has to be satisfied at the time of landing. Under this kind of a discontinuous ITQ system the profit function for a fishing trip lasting for the period $[0,T]$ may be written as:

$$\pi = \Sigma_i p(T) \cdot l(T) \cdot exp(-rT) - \int_0^T [CE(e) + \Sigma_i (CL(y - d) + CD(d)) + s \cdot z] \cdot exp(-rt)dt, \tag{16}$$

where to simplify the notation redundant indices and arguments have been suppressed.

The variables e, $d(i)$, $i = 1, 2, \ldots I$, and z in (16) are control variables. $l(t)$, $q(t)$ and $x(t)$ are state variables. $l(t)$ now represents the accumulated retained catch at time t. Clearly $\Sigma_i p(i,T) \cdot l(i,T)$ is the value of the landed catch at time T and $\Sigma_i p(T) \cdot l(T) \cdot exp(-rT)$ the corresponding present value. $q(t)$ represents the quota holding at time t and $x(t)$ the biomass level. However, as the shadow value of the biomass normally plays a minimal role in the behaviour of private firms,[20] we will ignore the biomass constraint in what follows. The integral in (16) represents the present value of operating costs during the fishing trips including the costs of retaining and discarding catch of the various grades.

During the fishing trip $l(t)$ clearly accumulates according to the equation:

$$\Sigma_i \partial l(i)/\partial t = \Sigma_i [Y(e,x,i) - d(i)] \tag{17}$$

The path of quota holdings, $q(t)$, is given by (12) above. The quota constraint is now simply the terminal condition:

$$q(T) \geqslant \Sigma_i l(i,T). \tag{18}$$

Firm j seeks to adjust $e(j)$, $\boldsymbol{d}(j)$ and $z(j)$ to maximize (16) subject to the constraints expressed in (12), (17) and (18) and the nonnegativity constraints $q(t), e(\mathrm{j}), \boldsymbol{d}(\mathrm{j}) \geqslant 0$.

The solution to this problem includes the discarding rule:[21]

$$d(i,j) > 0 \text{ if } CL_l(y(i) - 0) - CD_d(0,i) > [p(i) - \sigma(T)] \cdot exp(-r(T - t)), \text{ all } i, \tag{19}$$

where $\sigma(T)$ is the shadow value of the quota constraint at time T.

The discarding rule expressed in (19) slightly modifies the discarding rule for the continuous ITQ system discussed above. The modification consists of the addition of the discount factor $exp(-r(T - t))$. This term clearly increases in t. Thus, according to (19), the tendency to discard is at a maximum at the beginning of a fishing trip and diminishes as the time of landing approaches. This appears to be economically plausible. At the landing time, $t = T$, the quota constraint becomes effective and the two discarding rules (19) and (14) coincide.

[20] See the arguments concerning $\delta(i)$ in the previous subsection.
[21] Another noteworthy feature of the maximizing solution is that quota holdings during fishing trips require that the quota price path follows the Hotelling rule, i.e., $\partial s/\partial t = r \cdot s$.

Numerical Examples

The socially optimal discarding function is given by equation (9):

$$\Gamma(i) = CL_l(y(i) - 0,i) - p(i) - CD_d(0,i) \tag{9}$$

Similarly, the discarding function for the continuous ITQ system is given by equation (15):

$$\Gamma(i) = CL_l(y(i) - 0,i) + \Omega(j) - p(i) - CD_d(0,i), \tag{15}$$

where, ignoring firm j's imputed value of biomass, $\Omega(j)$ represents the firm's shadow value of quota. To illustrate the application of this equation let us resort to some simplifying assumptions.

The instantaneous profit function of firm j under an ITQ system may be written as:

$$\pi = \Sigma_i p(i) \cdot l(i) - CE(e) - \Sigma_i(CL(l(i),i) - CD(d(i),i) - s \cdot z$$

Now, landings correspond to quota use. This latter variable has been previously referred to as q. Clearly,

$$\Sigma_i l(i) \equiv \Sigma_i(y(i) - d(i)) \equiv q.$$

Consequently, we may write the instantaneous marginal profits of quota use as:

$$\partial\pi/\partial q = \Sigma_i p(i) \cdot \partial l(i)/\partial q - CE_q - \Sigma_i CL_l \cdot \partial l(i)/\partial q,$$

where $CE_q \equiv CE_e \cdot \partial e/\partial q$, where $e = E(\Sigma_i y(i),\mathrm{x})$ is the fishing effort necessary to harvest the total volume of landings, $\Sigma_i l(i)$.

Ignoring capital gains and losses on quota holdings, the firm's instantaneous marginal profits of quota use equals its instantaneous shadow value. More precisely:

$$\Omega(j) = \partial\pi/\partial q$$

Now, the term $\partial l(i)/\partial q$ indicates the grade distribution in the marginal aggregate landings, q. Clearly, $\Sigma_i \ \partial l(i)/\partial q = 1$. Consequently the $(\partial l(i)/\partial q)$s are weights. Correspondingly we define the (landings) weighted averages:

$$p^\circ \equiv \Sigma_i p(i) \cdot \partial l(i)/\partial q$$

$$CL_l^\circ \equiv \Sigma_i CL_l \cdot \partial l(i)/\partial q$$

Given all this, we may rewrite $\Omega(j)$ as

$$\Omega(j) = \partial\pi/\partial q = p^{\circ} - CE_q - CL_l^{\circ}.$$

Substituting this expression for $\Omega(j)$ in (15), firm j's discarding function may be rewritten as:

$$\Gamma(i) = [p^{\circ} - p(i)] - [CL_l^{\circ}(\mathrm{i}) - CL_l(i)] - C_q - CD_d(i). \tag{15'}$$

According to (15′), the decision to discard function depends on four sets of variables; (a) the price of landings of grade i compared to the weighted average price over all grades, (b) the handling and landing costs of grade i compared to the weighted average of this cost over all grades, (c) the marginal cost of harvesting and (d) the marginal cost of discarding. In accordance with economic intuition, the tendency to discard catch of grade i decreases with its price, marginal harvesting costs and discarding costs and increases with its handling and landing costs.

Let us now employ (15′) to illustrate further the quantitative nature of the discarding function under the ITQ management regime. For the purpose of illustration let us assume that the cost terms in (15′) are all independent of grades as follows:

$$C_q = a \cdot p^{\circ},\ a \in [0,1] \tag{i}$$

$$CD_{d(\mathrm{i})} = b \cdot p^{\circ},\ b \in [0,1] \tag{ii}$$

$$[CL_l^{\circ}(i) - CL_{l(i)}(i)] = c \cdot p^{\circ},\ \mathrm{c} \in [0,1] \tag{iii}$$

Given these assumptions, it is a simple matter to calculate the $p(i)/p^{\circ}$ ratios that make the discarding function zero. The relevant equation is:

$$p(i)/p^{\circ} = 1 - \mathrm{a} - \mathrm{b} - \mathrm{c}. \tag{20}$$

Plugging the appropriate values for the parameters a, b and c into this equation yields the $p(i)/p^{\circ}$ ratio that makes the discarding function zero. Thus, for instance assuming that for a specific grade a = 0.4, b = 0.1 and c = 0.1, equation (20) yields $p(i)/p^{\circ} = 0.4$. This means that the fisher would be indifferent between keeping and discarding fish of this grade if the price was 40% of the weighted average price over all grades. A slightly lower $p(i)$ would imply discarding.

For a final illustration, let us compare examples of discarding functions for the two management regimes, *i.e.*, the competitive fishery defined by equation (9), and the ITQ managed fishery defined by equation (15′). For this purpose let us consider a stylized version of the Icelandic cod fishery.

The Icelandic cod fishery consists of many year classes. Landing prices depend *inter alia* on fish size. In fact, the smallest fish, consisting of the youngest year classes fetch a very low price at the quay side. In addition, the very large cod, being difficult to process, also carries a slight negative price premium. In the

Icelandic cod fishery, approximate values for the relevant entries in the two discarding functions may be taken to be:[22]

$$C_q = a \cdot p^\circ,\ a \approx 0.4 \tag{i}$$

$$CD_{d(i)} = b \cdot p^\circ,\ b \approx 0.01 \tag{ii}$$

$$CL_{l(i)} = d \cdot p^\circ,\ d \approx 0.2 \tag{iii}$$

$$[CL_l^\circ(\mathrm{i}) - CL_{l(i)}(i)] = c \cdot p^\circ,\ c \approx 0.0 \tag{iv}$$

Given these specifications, we may rewrite the discarding functions for the competitive and the ITQ fishery respectively as follows:

$$\Gamma(i)/p^\circ = 0.19 - p(i)/p^\circ, \tag{9'}$$

$$\Gamma(i)/p^\circ = 0.59 - p(i)/p^\circ. \tag{15''}$$

Note that the dependent variable of these two equations, $\Gamma(i)/p^\circ$, has the convenient property of being independent of units of measurement. We refer to this variable as the discarding value. A positive discarding value implies discarding of that particular grade and vice versa. More generally, the numerical value of the discarding value may be regarded as a measure of the tendency to discard or keep catch of the grade in question.

Data on cod prices by cod size may be obtained from official and private fish market sources.[23] Given these estimates of the $p(i)/p^\circ$ ratio, discarding values for this stylized example of the Icelandic cod fishery are easily calculated. The results are illustrated in Figure 3.

As shown in Figure 3, the ITQ discarding function strictly dominates the competitive one. In fact the difference is quite pronounced. In this respect, however, the very approximate nature of both our model and the quantitative data should be kept in mind. Due to gear selectivity in the Icelandic cod fishery very few cod younger than 3 years are actually caught. Consequently there appears to be very little tendency to discard even under the ITQ system. This is in accordance with the available measurements on discarding in the Icelandic cod fishery discussed in the introduction to this paper.

Potential Remedies

The usual ITQ fisheries management systems create a tendency for excessive discarding of catch. The magnitude of the inefficiency depends on the parameters of the situation but may be substantial. Excessive discarding of a particular grade of fish generally decreases with the relative price of the grade and harvesting and

[22] The parameter values employed are based broadly on official publications on the economics of the Icelandic cod fishery. See especially National Economic Institute (1991) and the Fisheries Association (1992).

[23] These data are only to a limited extent available in official publications but may be obtained from *e.g.* Verdlagsrad Sjavarutvegsins and Faxamarkadur.

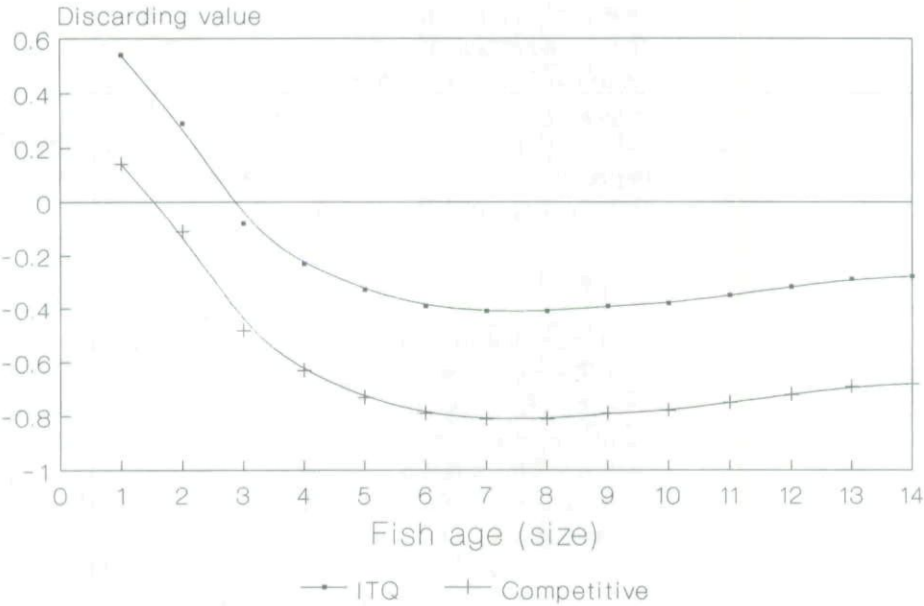

Figure 3. Discarding functions for two management regimes: A stylized version of the Icelandic cod fishery.

discarding costs. It increases, on the other hand, with the relative handling and landing costs of the grade in question.

Three rather obvious remedies of the discarding problem may be suggested:

ITQs By Grades

If ITQs are issued for each grade, the quota price for each grade will reflect the relevant economics of harvesting, processing and marketing that grade. In that case, the quota prices will never induce excessive discarding of catch. For instance for a marginal grade—*i.e.* a grade that would be marginally discarded under a competitive fishery—the quota price would obviously be zero. Hence, the quota price would constitute no extra incentive to discard that catch.

The issue of ITQs by grades, however, is hardly a practical solution in most cases. There are many problems. First, the grades may be numerous and probably time variant as well. Second, as the number of grades increases, the market for each may become very thin. Third, enforcement of quota rights by grades may easily prove prohibitively costly.

Nevertheless, ITQs by catch grades appear to constitute an interesting option. In some fisheries, especially those with few, easily detectable grades, such a system may turn out to be beneficial.

Taxes and Subsidies

Catch discarding is an externality problem. Therefore, the Pigovian solution of imposing the appropriate taxes and subsidies may be economically justified.

The construction of such a tax system must be done with proper care, however. In particular, reduction of the quota price by imposing landings or quota use taxes is probably not going to work. The reason is that this method reduces both sides of the discarding inequality, *i.e.* $p(i)$ and $\Omega(i)$ equally. On the other hand property taxes on quota values or selective price subsidies on inferior grades will in theory do the trick. The problem, as always in the case of Pigovian taxes, is to select the (approximately) correct tax or subsidy rate.[24]

Enforcement

Excessive discarding may be regarded as violation of fishery property rights. In fact, irrespective of whether it is excessive or not, discarding often seems to be regarded as such. From this point of view, the problem becomes one of enforcement. The problem of the enforcer is to select the socially optimal combination of enforcement effort and sanctions. This raises a range of issues. For instance, to be able to select the socially optimal combination of enforcement effort and sanctions the enforcer must know the response function of the fishing firms to enforcement activity. Since this information requires, among other things, measurements of the actual level of discarding, it is in general very hard to come by. A more promising approach is to attempt the design of a market generated enforcement activity.

Given the intricacies of the discarding problem it appears unlikely that one general solution exists. It may well be the best practical line of action is to employ a mix of some or all of the methods discussed above.

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