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On the Microeconomics of Quota Management in Fisheries

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Abstract *This paper compares the economic incentives created by transferable and non-transferable quotas in a fishery, in particular the incentives to discard fish of certain species or grades when quotas are enforced at the landing site. With a hypothetical efficient allocation of non-transferable quotas, the incentive structure is essentially the same as under transferable quotas. However, in the absence of the information provided by the quota price, outcomes may not be the same under all conditions. Inefficient allocations of non-transferable quotas will tend to reduce discards due to highgrading but increase discards in multispecies fisheries. The impact of discarding on the quota price in a transferable quota fishery is examined.*

Key words Fisheries management, quotas, ITQs, discards.

JEL Classification Codes D21, D45, Q22.

Introduction

Quota management is widely employed in fisheries in order to achieve conservation and (in some cases at least) efficiency objectives. Although much attention in recent years has focused on the market allocation of quotas, in particular on systems of individual transferable quotas (ITQs), in many countries quotas continue to be allocated wholly or partially by other means.[1] Despite the efficiency arguments for transferable quotas (*e.g.*, Arnason 1990, Clark 1990), faced with the possible transition from an existing non-market allocation of quota to a market-based system, management authorities may be as concerned with the consequences for the enforcement of landings and for levels of discards as with the allocative efficiency of the fishery.[2]

The aim of this paper is to analyse and compare the incentives created by transferable and non-transferable quotas, in particular the incentives to remain within quota limits by discarding elements of the catch prior to landing. The role of enforcement in assuring that quotas are respected at the landing site is explicitly considered. Clearly, both over-quota landings and discards are of serious concern for the management authority, since a total allowable catch (TAC) which appears to

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[1] Within the European Union, only in the Netherlands are national quotas allocated using an ITQ system; other EU member states rely principally on non-market mechanisms to allocate quotas, such as monthly quota limits or non-transferable annual quotas.

[2] This has certainly been the experience with EU fisheries, including recent discussions around ITQs initiated by the European Commission. The United Kingdom Government has also recently been led by *impromptu* quota trading by the industry to consider seriously the potential benefits and costs of a formal ITQ system (see Hatcher and Read 2001, Hatcher *et al.* 2002).

have been complied with may, in reality, have been exceeded by a significant (and unknown) margin.

The basic economics of discarding in fisheries are examined by Anderson (1994a, 1994b) and Arnason (1994). Both Anderson (1994a) and Arnason (1994) emphasise that the necessary condition for discarding is that there is some differentiation in the catch and the sufficient condition is then that the unit costs of retaining and landing a part of the catch exceed the corresponding market price. Arnason (1994) finds that, to the extent that an ITQ system introduces an (additional) opportunity cost for each unit of fish landed (the quota price), all else equal, incentives to discard are increased under ITQs compared to a free-access fishery.[3] Anderson (1994b) compares incentives to discard particular grades of fish with a capacity (hold) constraint and with ITQs, noting the theoretical equivalence of the shadow price on the physical constraint and the ITQ price.[4] Similarly, Vestergaard (1996) compares such highgrading incentives under non-transferable quotas and ITQs, concluding that, all else equal, discards will increase (decrease) under ITQs if the quota price is greater (smaller) than the shadow price of the non-transferable quota. All these studies, though, confine themselves to cases where there are just two elements to the catch. Further, the discard incentives which arise in multispecies quota fisheries due to quota/catch mismatches at the vessel level (*e.g.*, Squires 1987, Kirkley and Strand 1988, Squires *et al.* 1998) have not been studied in any detail. Experience suggests, however, that in multispecies fisheries, managers (and indeed fishermen) are greatly concerned about discards due to vessels not holding quota in the same proportions as species appear in the catch.

This paper extends analysis of the microeconomics of quota management in order to gain greater insight into potential outcomes under non-transferable and transferable quota regimes, including the implications of discarding for the quota price in a transferable quota fishery. The paper is structured as follows. The next section develops a simple short-run model of vessel behaviour with an output (quota) constraint, which is then allowed to be transferable. The third section examines incentives for discarding in a multispecies fishery with transferable and non-transferable quotas, while the following section considers highgrading; *i.e.*, discarding in a single-species fishery in which there are many grades of the same species. A final section contains some concluding comments.

The Basic Quota Model

Consider a fishing vessel operated as a single price-taking firm. To begin with, assume a single-species fishery with no price differentiation between any elements of the catch. In a given period, the firm's short-run profit function is:

$$\pi(q) \equiv pq - c(q),$$

where q is the catch and p is the unit price received for the catch at first sale (fish prices are assumed parametric to the firm and the fishery throughout).[5] Variable costs, c, are defined as a function of catch. It is assumed, implicitly in the profit function, that catch is a deterministic function of an unspecified variable input

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[3] This was, more or less, the result for individual quotas suggested by Copes (1976).
[4] *In the single species case only*, a hold constraint is analogous to a non-transferable quota that is perfectly enforced.
[5] For clarity, individual firm subscripts are omitted throughout.

(which we could call effort) and for simplicity can be treated as the choice variable. We assume increasing marginal costs of effort, and therefore catch; *i.e.*, $c''(q) > 0$, so that there is some finite level of catch at which short-run profits are maximised. Given this, the necessary condition for (unconstrained) profit maximisation is, as is usual, $d\pi/dq \equiv p - c'(q) = 0$.

Introducing a non-transferable catch quota, Q, presents the simple constrained optimisation problem:

$$\max_q \; pq - c(q) \quad \text{s.t. } q \leq Q.$$

The corresponding Lagrangian:

$$L = pq - c(q) - \lambda\left[q - Q\right]$$

yields the first order (Kuhn-Tucker) condition for profit maximisation:

$$p - c'(q) = \lambda. \tag{1}$$

Assuming the constraint binds, the Lagrange multiplier λ represents the shadow price of the quota; *i.e.*, $\lambda = \partial\pi/\partial Q$, which equates with marginal profit $[p - c'(q)]$ at the quota constraint. If equation (1) is rearranged as $p - \lambda = c'(q)$, the LHS term $(p - \lambda)$ can be thought of as the *virtual price* of constrained output (following Neary and Roberts 1980); *i.e.*, the output price at which the firm would choose freely to produce at $q^* = Q$. In essence, the fundamental short-run goal of a quota management system is to induce vessels to produce *as if* they faced an output price of $(p - \lambda)$ rather than p at some appropriate level of output. As we will see, the shadow price can be imposed as an actual or expected cost through a system of penalties or, in the case of transferable quotas, the market price for quota. In this respect, management by quotas is theoretically similar to the use of a tax to control output.[6]

In a real world fishery, some (or many) vessels will seek to catch more than the quota if it is profitable to do so (indeed all will if we assume strictly rational behaviour; *i.e.*, behaviour motivated solely by monetary costs and benefits). The fishery management authority is then faced with the task of enforcing compliance with quotas by imposing a penalty on vessels which violate. A monitoring system must detect infringements, and the judicial system must then impose penalties of an appropriate size. Let the resultant expected fine for a violation $q > Q$ be $F(q)$ with $F''(q) \geq 0$.[7] Now (for a risk-neutral firm) expected profits are maximised where:

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[6] Clark (1985) makes a similar point in the context of ITQs, as does Boyce (1996). The distinctions primarily concern the distribution of short-run profits. With an output tax, a management authority receives part of the revenue on every unit of production. With transferable quotas there is an opportunity cost for every unit of quota used, part of which might be paid to the management authority if there is a quota or revenue charge as a means of rent capture (*e.g.*, Grafton 1995). With a perfectly enforced non-transferable quota, however, all profit from production up to the quota limit is retained by the firm.

[7] The modeling of enforcement here derives from the utilitarian approach of Becker (1968); see Sutinen and Andersen (1985); Anderson and Lee (1986); and Charles, Mazany, and Cross (1999) for fisheries applications. The expected fine $F(\cdot)$ depends upon the probability of detection and sanction and the anticipated penalty if sanctioned. In practice, the management authority may face difficulties including political or judicial resistance to the imposition of larger financial penalties for fishing offences as well as the costs and decreasing marginal returns of increasing enforcement effort and the probability of detecting offences. See, for example, Sutinen and Andersen (1985), Anderson and Lee (1986), Milliman (1986), and Anderson (1989).

$$p - c'(q) = F'(q). \tag{2}$$

Note that $F'(q)$, the expected marginal fine as a function of catch, neatly replaces the λ in equation (1). Effective enforcement of the quota; *i.e.*, production at $q^* = Q$, requires that the expected marginal fine for the first unit of violation is at least as large as the shadow price, λ (and is non-decreasing for further units of violation).[8]

Now let quotas be transferable. In the short run, the firm can vary its quota allocation by buying (or selling) quota at the prevailing market price.[9] The firm's maximisation problem becomes:

$$\max_{q,Q} \; pq - c(q) - rQ \quad \text{s.t. } q \le Q,$$

where r is the short-run (rental) price of quota. The first-order conditions for q^*, $Q^* > 0$ are equation (1) together with $r = \lambda$. Solving for λ, we have the standard decision rule for transferable quotas:

$$p - c'(q) = r, \tag{3}$$

which, as we see, implicitly assumes that r is equated with λ. The most important implication of a transferable quota from the individual firm's short-run decision-making perspective is that there is now a choice between landing a marginal unit of fish illegally or purchasing an additional unit of quota. It is apparent, however, that a strictly rational firm will only buy quota if it is less costly than the expected fine incurred if the fish was landed without quota. In other words, for equation (3) to hold in practice requires that enforcement is such that the expected marginal fine for landing over-quota fish is always equal to or greater than λ.[10] We will make this assumption from now on, but it should be remembered that incentives for discarding are contingent upon the enforcement of landings controls.

Quotas and Discarding in a Multispecies Fishery

Now consider a vessel firm in a multispecies fishery. Let there be m species in the fishery (indexed $i = 1,2,\ldots m$), which are always caught in the same proportion; *i.e.*, there is no random variation in the catch composition, nor can the vessel selectively target particular species or otherwise alter the catch composition.[11] Let β_i be the proportion of the ith species in the catch, so that $\sum_{i=1}^{m}\beta_i = 1$ and $q = \sum_{i=1}^{m}\beta_i q$, and let there be m associated quotas $Q_1, Q_2,\ldots Q_m$. As before, assume that each species is an

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[8] The requirement for $F''(\cdot) \ge 0$ is effectively a statement of the legal principal of marginal (and cumulative) deterrence (Shavell 1992).

[9] It is assumed that the vessel has no initial endowment of quota. Given that in the quota market unused quota has an opportunity cost equal to the price at which quota must be bought, this does not affect the results obtained. This would not be true, however, in the case where one or more firms enjoys market power in the quota market (see Anderson 1991).

[10] As Malik (1990) and Keeler (1991) discuss in the context of tradeable pollution permits, given certain assumptions about the form of the expected penalty function, if all vessels in the fishery behaved strictly rationally, a quota price *greater* than the expected marginal fine at the optimum level of catch would not be observed since the market price for quota would then simply fall to the level of the expected marginal fine. We would then have the same decision rule whether vessels in the fishery are compliant or not.

[11] The restrictiveness of this assumption, and the possible implications of relaxing it, are discussed later.

undifferentiated product and commands a constant market price p_i. We now assume (as is most often the case in practice) that *catches* cannot be observed by the authority but landings can. The quota constraints, therefore, have to be formulated in terms of landings rather than catches. This introduces an additional set of choice variables: the level of discards of each species. The quota constraint for the *i*th species becomes $\beta_i q - d_i \leq Q_i$, where d_i is the quantity of the catch of that species which is discarded prior to landing.[12]

Non-transferable Quotas

With non-transferable quotas, the firm's constrained maximisation problem is now:

$$\max_{q,d_i} \sum_{i=1}^{m} p_i\left[\beta_i q - d_i\right] - c(q) \quad \text{s.t.} \quad \beta_i q - d_i \leq Q_i \quad \text{and} \quad d_i \leq \beta_i q,$$

where the second constraint ensures that the vessel cannot discard more of the *i*th species than it catches. Letting μ_i be the Lagrange multiplier on the *i*th such discarding constraint, we have the following first-order conditions for $q^*, d_i^* > 0$:

$$\sum_{i=1}^{m} p_i\beta_i - c'(q) + \sum_{i=1}^{m} \mu_i\beta_i = \sum_{i=1}^{m} \lambda_i\beta_i \tag{4}$$

and

$$p_i + \mu_i = \lambda_i, \quad i = 1, 2, \quad , m. \tag{5}$$

The Lagrange function and the Kuhn-Tucker conditions for an optimal solution are shown in full in Appendix A (equations A-1). Note, firstly, that for any species for which the vessel has a non-zero quota allocation, the multiplier μ_i is zero (since there will never be a situation in which *all* individuals of that species will be discarded); secondly, that the discarding condition (5) cannot hold until and unless a species quota is filled and the multiplier λ_i becomes positive. Given this, if at the optimum level of catch the discard condition (5) holds for *k* of the *m* species in the catch, then for the marginal unit of catch we can write:

$$\sum_{i=k+1}^{m} p_i\beta_i - c'(q) = \sum_{i=k+1}^{m} \lambda_i\beta_i, \tag{6}$$

where we have first multiplied both sides of equation (5) by β_i and then subtracted *k* of these conditions from equation (4). Equation (6) states that, at the optimum level of catch, the marginal profit from the last unit of catch, less the market value of that

[12] For simplicity, it is assumed that the process of discarding (and indeed the process of landing fish) is a costless activity. This does not substantially affect the results, but it does reduce the complexity of the equations throughout. Note that if landings costs equaled the costs of discarding, these costs would cancel out in any case.

part of the marginal unit of catch which is discarded (*i.e.*, all fish of species $1,2,\ldots k$), equals the shadow price of quota for those $m - k$ species which are not discarded (this will be zero with respect to those species quotas which are unfilled). If we assume that the expected marginal fine for landing over-quota fish is everywhere equal to (or exceeds) the shadow price of quota, then equation (6) will hold in practice, and all quotas will be complied with at the point of landing.

If quotas are allocated to the vessel in exactly the same proportion as the species appear in the catch, then all quotas will be filled at the same level of catch. If the expected marginal fine for the first unit of a violation is high enough to equal or exceed the shadow price at the point where all quotas are just filled, we will have compliance. Clearly, increasing the catch further cannot be profitable, since the retention of additional fish of any species would increase the expected fine more than profits. Under these conditions there will be no discarding because of quotas.

If quotas are allocated in *different* proportions to those in which species appear in the catch, then the quotas will be filled sequentially at different levels of catch.[13] For the *i*th species quota filled, the discard condition (5) will hold in practice if p_i is equaled (or exceeded) by the expected marginal increase in the fine from retaining and landing an additional unit of that species (or, equivalently, the expected marginal reduction in the fine from discarding a unit of that species). Note that here the shadow price of the quota, λ_i (and hence the expected marginal fine) is simply equated with p_i, and the marginal cost of effort/catch is not involved in the decision to discard. The catch is increased further, but with fish of the *i*th species being discarded, until condition (6) holds, as described above. How many species discarded from the marginal unit of catch at the optimum will depend on the size of quotas in relation to the vessel's capacity, the composition of the catch, and the relative market price of each species. Note that if, at the optimum, it is not profitable to increase the catch further in order to fill any remaining unfilled quotas, the RHS of equation (6) will be equal to zero.

Figure 1 illustrates the simplest two-species case. The curve MP_{1+2} traces out the firm's marginal profit as a function of catch with both species 1 and species 2 retained. The MP_2 curve is the marginal profit with only fish of species 2 retained. The quota for species 1 is filled at a catch level of q^0. With perfect enforcement of landings, catch is increased along the path abcd (discarding fish of species 1) with the quota for species 2 filled at catch q^*. Short-run profits are given by the area 0abcde.

Transferable Quotas

In a multispecies transferable quota fishery, the firm's profit maximisation problem is:

$$\max_{q,d_i,Q_i} \sum_{i=1}^{m} p_i\left[\beta_i q - d_i\right] - c(q) - \sum_{i=1}^{m} r_i Q_i \quad \text{s.t.} \quad \beta_i q - d_i \le Q_i \quad \text{and} \quad d_i \le \beta_i q,$$

where r_i is the short-run price of quota Q_i for the *i*th species. From the Kuhn-Tucker conditions shown in Appendix A (equations A-2), we now have three first-order conditions (for $q, d_i, Q_i > 0$) which are, respectively, equations (4) and (5), together with:

[13] Boyce (1996) recognises this problem in the context of TACs for a target species and a bycatch species but does not allow for either discarding or cheating in his model.

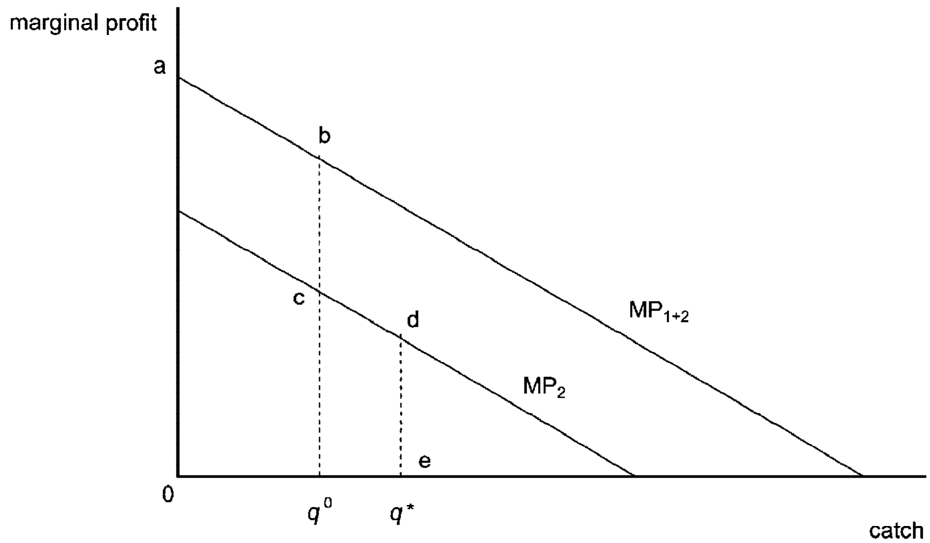

Figure 1. Non-transferable Quotas in a Two-species Fishery

$$r_i = \lambda_i, \quad i = 1, 2, \quad , m. \tag{7}$$

From equations (4) and (7), and assuming no discarding, we have the decision rule:

$$\sum_{i=1}^{m} p_i\beta_i - c'(q) = \sum_{i=1}^{m} r_i\beta_i, \tag{8}$$

where $\sum_{i=1}^{m} r_i\beta_i$ is the price of quota for the marginal unit of catch. Solving equations (5) and (7) for λ_i, the condition for discarding is:

$$p_i + \mu_i = r_i, \quad i = 1,2,...m, \tag{9}$$

that is, the market price for fish of a given species is just equal to (or less than) the quota price. Note that, as before, the μ_i will be zero unless the discard constraints bind.

With active trading in quota, a quota price greater than the selling price of the fish is rather unlikely. Nevertheless, if for some reason the quota price *were* greater than the fish market price for k species in the catch, these species would be discarded from each and every unit of catch, and quota would only be purchased to cover the catches of the $m - k$ species which are retained and landed. If we multiply equation (9) by β_i and subtract k of these equations from (4), at the same time substituting r_i for λ_i, we have:

$$\sum_{i=k+1}^{m} p_i\beta_i - c'(q) = \sum_{i=k+1}^{m} r_i\beta_i, \tag{10}$$

where the μ_i are zero for the $m - k$ retained species and are, therefore, dropped. Equation (10) simply states that at the optimum level of catch, the profit from the marginal unit of catch (less the value of the discarded part of the catch) equals the price of quota for the retained part of the catch.

Figure 2 illustrates this for the two-species case. With the market price for species 1 (p_1) less than the corresponding quota price (r_1), all fish of species 1 are discarded. The optimal level of catch q^* is then where the cost of quota for the retained species ($r_2\beta_2$) is just equaled by the marginal profit from the retained catch MP_2. The optimal quota demand is equivalent to Q_2^*, and short-run profits are given by the area abc.[14]

Transferable and Non-transferable Quotas Compared

In a transferable quota fishery, a vessel can only produce according to equation (8) if the total species quotas available to the fishery as a whole occur in exactly the same proportions as the species appear in the catch. Otherwise, at the equilibrium (efficient) quota allocation, condition (8) cannot possibly hold for every vessel in the fishery. Letting Ω_i be the total quota or TAC for the ith species, if we have, say, $\Omega_1 / \sum_{i=1}^{m} \Omega_i < \beta_1$, then at least some vessels will be unable to obtain sufficient quota for species 1 to operate according to equation (8). Instead, they will operate where, at the margin:

$$\sum_{i=2}^{m} p_i\beta_i - c'(q) = \sum_{i=2}^{m} r_i\beta_i,$$

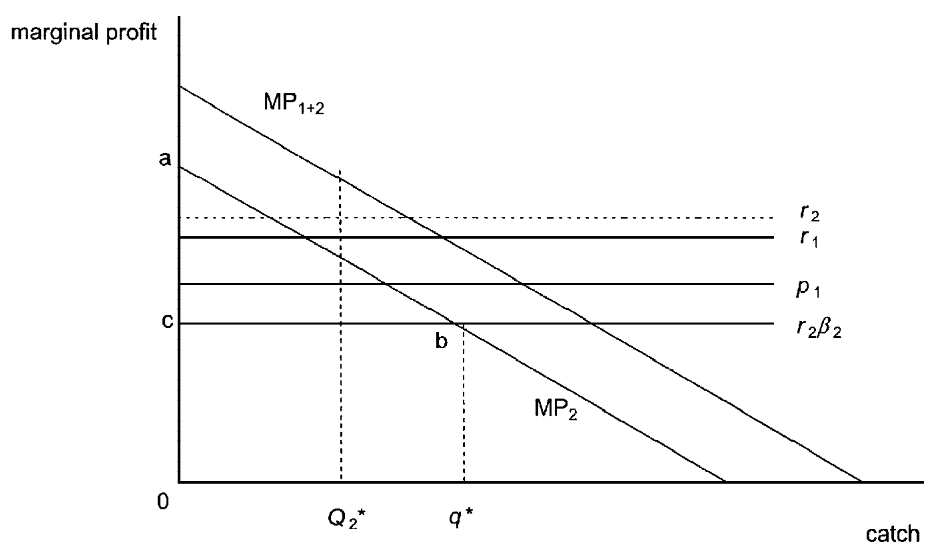

Figure 2. Transferable Quotas in a Two-species Fishery

[14] Note that we cannot infer the quota price for species 2 (r_2) directly from the marginal profit curves.

i.e., according to condition (10). In this case, however, not *all* fish of species 1 will be discarded, only those for which the vessel is unable to obtain quota. In effect, we now have condition (6) for the optimal catch with *non-transferable* quotas, except that the r_i replace the λ_i for the $i = 2,\ldots m$ species quotas which are relatively unconstrained in their supply.[15]

If the TACs are not set in proportion to the occurrence of species in the catch, we can find that discarding may be the same, or may be increased, under a system of non-transferable quotas, depending on how far the allocation of quota differs from the efficient allocation we would expect under transferable quotas. To see this, let $Q_1 = q\beta_1$ be a vessel's optimal demand for quota for species 1 (at the optimum catch q^*) when quotas are transferable. Now let the TAC for species 1 be constrained relative to the other species' TACs in the fishery, so that the vessel is only able to obtain $\tilde{Q}_1 < Q_1$ units of quota for this species.[16] At the efficient quota allocation (which, as argued below, implies the same optimum catch as when the TAC for species 1 is not constrained), there will then be $Q_1 - \tilde{Q}_1$ discards of fish of species 1. Suppose that we have a non-transferable quota allocation which mirrors the efficient allocation, except that the allocation of Q_1 to two similar vessels deviates from $\tilde{Q}_1$ by no more than $\pm[Q_1 - \tilde{Q}_1]$ units. The *total* volume of discards of species 1 would then be unaltered across the two vessels. If, however, the allocation of Q_1 deviated from $\tilde{Q}_1$ by more than this, the total volume of discards of species 1 would be increased. Not only this, there could also be increased discards of other species. Consider where one vessel is allocated $\overline{Q}_1 > Q_1$ units of quota for species 1, so that total discards of species 1 across both vessels are increased by $[\overline{Q}_1 - Q_1]$ units. If it were profitable for the vessel now to increase its catch by $[\overline{Q}_1 - Q_1]/\beta_1$ units in order to fill the extra quota it has for species 1, it would need to discard $[\overline{Q}_1 - Q_1]/\beta_1\ [1 - \beta_1]$ units of fish of the other species.

Discarding and the Quota Price

In a transferable quota fishery, the undersupply of one species' TAC relative to the TACs of other species will have an impact on the quota price for those other species. If, at the optimum, condition (10) holds, then assuming that the market for all quota has cleared, we must have the same optimal catch as when the optimum condition is equation (8) (the *absolute* quantities of the other species TACs, we have assumed, are unchanged). Since this implies the same marginal cost for the vessel, we can solve for this and write:

$$\sum_{i=1}^{m} p_i\beta_i - \sum_{i=1}^{m} r_i\beta_i = \sum_{i=2}^{m} p_i\beta_i - \sum_{i=2}^{m} \bar{r}_i\beta_i,$$

where the $\bar{r}_i$, $i = 2,3,\ldots,m$ are the quota prices at the optimum when Q_1 is undersupplied. If we rearrange this to:

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[15] With a relative undersupply of quota for species 1, it might be argued that the quota price for this species would then be bid up. At the limit, however, if $r_1 = p_1$ the individual vessel would be indifferent between discarding and not discarding fish of species 1 and would ignore r_1 in its production decision. The effect, in any case, is that Q_1 becomes fixed at less than the optimal demand Q_1.

[16] Assume that the other TACs are unchanged in nominal terms (although, of course, their proportions in the overall parcel of TACs will be increased).

$$\sum_{i=2}^{m} r_i\beta_i - \sum_{i=2}^{m} \bar{r}_i\beta_i = p_1\beta_1 - r_1\beta_1, \tag{11}$$

then provided $p_1 > r_1$ when Q_1 is *not* under-supplied, we must have:

$$\sum_{i=2}^{m} r_i\beta_i > \sum_{i=2}^{m} \bar{r}_i\beta_i,$$

i.e., the quota prices for species $i = 2,3,\ldots m$ are reduced due to the constrained supply of quota for species 1.[17] This is not surprising, since the *unit* costs of catching and landing fish of these other species are effectively increased.

"Highgrading" within Species Quotas

The problem of a species quota where different grades of fish of the same species (different sizes, most commonly) command different market prices, appears in the one-species case structurally similar to the multispecies problem, except that the quota constraint is expressed as $\sum_{j=1}^{n}[\beta_j q - d_j] \le Q$, where subscript j indexes the grade of fish ($j = 1,2,\ldots n$). As in the multispecies case, we assume that the vessel cannot select the catch composition.

Non-transferable Quotas

With a non-transferable species quota, the firm's maximisation problem is:

$$\max_{q,d_j} \sum_{j=1}^{n} p_j\left[\beta_j q - d_j\right] - c(q) \quad \text{s.t.} \quad \sum_{j=1}^{n}\left[\beta_j q - d_j\right] \le Q \quad \text{and} \quad d_j \le \beta_j q.$$

From equations (A-3) in Appendix A, the first-order conditions for $q, d_j > 0$ are:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q) + \sum_{j=1}^{n} \mu_j\beta_j = \lambda \tag{12}$$

and

$$p_j + \mu_j = \lambda, \quad j = 1,2,\ldots n. \tag{13}$$

Once the quota is filled, assuming the expected marginal fine for a first unit of a violation is high enough to deter any over-quota landings (*i.e.*, is at least equal to λ), the discard condition (13) will determine whether a unit of the least valuable fish

[17] This includes the possibility that one or more of the r_i fall to zero as vessels no longer find it profitable to catch the TAC.

already caught and retained will be discarded to allow a marginal increase in the catch. Clearly, as Anderson (1994b) notes for the two-grade case in the analogous setting of a hold constraint, it will only be profitable to do this if the marginal profit earned from the additional unit of catch is greater than the market price of the fish discarded. We examine this in more detail as follows. If a unit of fish of grade 1 is discarded at the optimum level of catch, we can solve for λ and rearrange to give:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q) = p_1 + \left[1 - \beta_1\right]\mu_1, \tag{14}$$

recalling that the μ_j are zero for the $j = 2,3,\ldots n$ grades which are *not* discarded. Note that the multiplier μ_1 on the discarding constraint for grade 1 represents the marginal value, at the optimum, of relaxing the constraint so that an additional unit of fish of this grade can be discarded (and hence, implicitly, allowing a further marginal increase in catch). Given this, the appearance of the $[1 - \beta_1]$ term on the RHS of equation (14) requires some explanation. In the objective function, the discarding constraint on grade 1 must apply to *all* fish of grade 1 at the optimum; *i.e.*, including the β_1 fish of this grade in the marginal unit of catch. We could, therefore, write equation (14) as:

$$\sum_{j=2}^{n} p_j\beta_j - c'(q) + p_1\beta_1 = p_1 + \left[1 - \beta_1\right]\mu_1$$

and hence, with some rearranging,

$$\frac{1}{\left[1 - \beta_1\right]}\left[\sum_{j=2}^{n} p_j\beta_j - c'(q)\right] = p_1 + \mu_1. \tag{15}$$

Equation (15) is equivalent to Anderson’s (1994b) highgrading equation for a hold constraint, except that here we have generalised from the two-grade case and assumed the costs of discarding to be zero. We can infer from equation (15) that if the vessel sought at the margin to replace a unit of fish of grade 1 entirely with fish of other grades, it would have to expand its catch not by 1 unit but by $1/[1 - \beta_1]$ units. Since we have assumed that the vessel does not discard the marginal catch β_1 of grade 1, in equation (14) the multiplier μ_1 is divided by $1/[1 - \beta_1]$. Looking at it another way, at the margin the vessel has a net revenue loss of just $[1 - \beta_1]p_1$ and, therefore, the associated multiplier is reduced to $[1 - \beta_1]\mu_1$.

Equation (14) states that if, at the quota-filling level of catch, we have $p_1 < \lambda$, it is optimal to discard units of this grade and increase the catch further until the marginal profit from the last unit of catch just equals the market price of the least valuable grade in the hold, which here is p_1, plus the associated μ_1 term, if positive. If at this point not all fish of grade 1 have been discarded, then $\mu_1 = 0$ and hence:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q) = p_1,$$

as we would expect. If, however, all retained fish of grade 1 have been discarded at the optimum, then $\mu_1 > 0$ which implies:

$$\sum_{j=1}^{n} p_j \beta_j - c'(q) > p_1.$$

Here, there are no fish left to discard that have a market value less than the additional profit that could be earned from a marginal increase in the catch.[18]

Figure 3 illustrates the simple case of two grades of fish. The vessel's quota is filled at catch q^0. Fish of grade 1 are then discarded and the catch is increased to q^* at which point all fish of grade 1 have been discarded (except for those in the marginal unit of catch). This is the optimal level of catch and profits are 0abc (plus the value of the grade 1 fish in the marginal unit of catch). The vertical distance from the grade 1 price line (p_1) to the curve MP_{1+2} (arrowed) is equal to $[1 - \beta_1]\mu_1$. In the case of more than one grade of fish discarded, the analysis is less straightforward. In particular, whereas it might appear intuitively rational always to discard the *least* valuable grade first, this may not represent an optimal behaviour. This is discussed below, where we compare outcomes with transferable and non-transferable quotas.

Transferable Quotas

In the one-species quota case, the firm's maximisation problem with transferable quotas is:

$$\max_{q,\, d_j,\, Q} \sum_{j=1}^{n} p_j \left[\beta_j q - d_j\right] - c(q) - rQ \ \text{ s.t. } \sum_{j=1}^{n} \left[\beta_j q - d_j\right] \leq Q \ \text{ and } \ d_j \leq \beta_j q.$$

From equations (A-4) in Appendix A, the first-order conditions for $q, d_j, Q > 0$ are equations (12) and (13) together with:

$$r = \lambda. \tag{16}$$

Assuming that the expected marginal fine for a violation is high enough to deter over-quota landings, the condition for discarding is:

$$p_j + \mu_j = r, \quad j = 1,2,...n, \tag{17}$$

i.e., the market price for fish *of a given grade* is just equal to (or less than) the quota price. Where there is a wide disparity between the market prices received for fish of different grades, this is quite possible. If the discard condition holds for *k* grades in

[18] Note that with multiple species non-transferable quotas (and no price differentiation between grades), optimality required only that fish from the marginal unit(s) of catch were discarded. Optimality in this case, however (assuming that the discarding condition holds), requires that units of the least valuable grade of fish *already retained on board* are discarded. It is not difficult to see that the foregoing analysis generalises straightforwardly to the case of a non-transferable multispecies quota; *i.e.*, a quota covering more than one species of fish, where, as is most often the case, different species command different market prices.

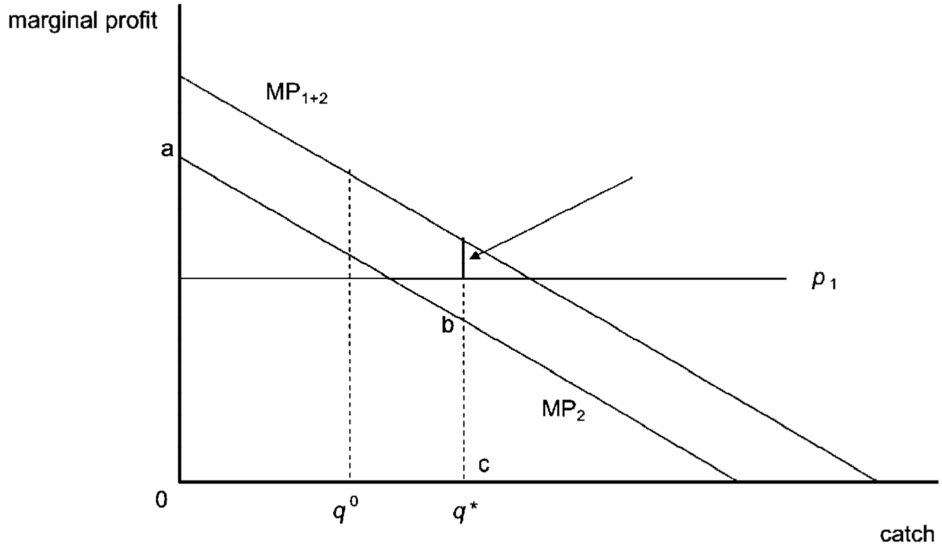

Figure 3. Non-transferable Quota with Two Grades of Fish

the catch, then these fish will be discarded from each and every unit of catch. Substituting *r* for λ in equation (12), then multiplying both sides of equation (13) by β_j and subtracting *k* of these conditions from equation (12), we have:

$$\sum_{j=k+1}^{n} p_j\beta_j - c'(q) = \sum_{j=k+1}^{n} r\beta_j \tag{18}$$

for the marginal unit of catch at the optimum (again recalling that the μ_j for the $n - k$ grades retained must be zero). The profit from the marginal unit of catch (given the discarding of *k* grades from the catch) just equals the cost of quota for that part of the marginal unit of catch that is retained.

The two-grade example is illustrated by figure 4. With the price of fish of grade 1 (p_1) less than the quota price (*r*), all fish of this grade are discarded, and the catch is increased to q^* where the cost of quota for the retained grade is just equaled by the marginal profit from the catch with only this grade retained. The optimal quota demand is equivalent to Q^* and profits are given by the area abc.[19]

Transferable and Non-transferable Quotas Compared

Vestergaard (1996) notes that the extent of highgrading with transferable and non-transferable quotas depends on the shadow price of the non-transferable quota compared to the transferable quota price. It can be shown (see Appendix B) that given a non-transferable quota allocation that is exactly equal to the optimal quota

[19] As before, in the diagram we cannot directly infer the quota price, *r*, from the marginal profit curves.

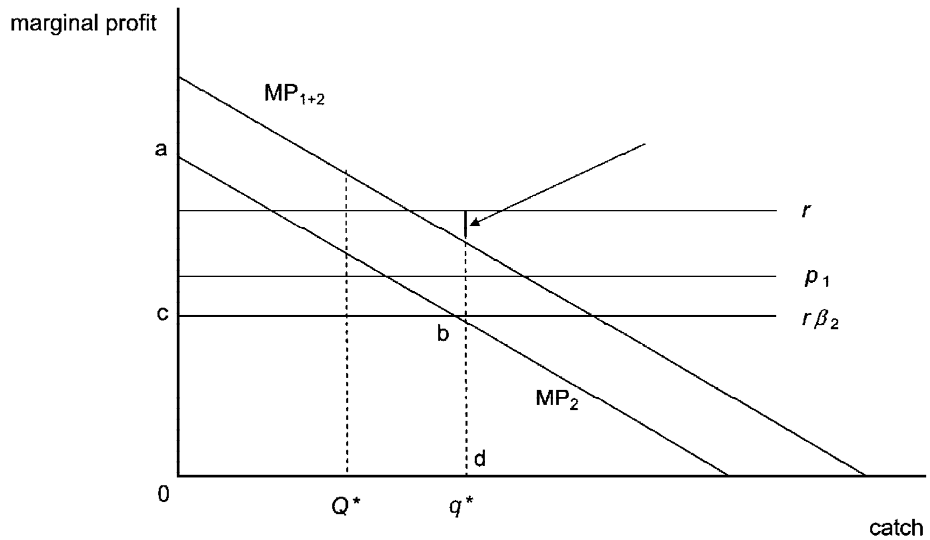

Figure 4. Transferable Quota with Two Grades of Fish

demand of a similar vessel under transferable quotas, the shadow price of the non-transferable quota is equal to the transferable quota price. If, from equation (13), we then have $p_1 + \mu_1 = \lambda$, the optimal catch and the optimal level of discards of grade 1 are the same. Here, all fish of grade 1 are discarded, so that $\mu_1 > 0$.

Looking again at figure 4, if the vessel has a non-transferable quota equal to Q^* it will discard all fish of grade 1 and increase the catch to q^* at which point there are no more fish of grade 1 left to discard. Note that with a non-transferable quota, profits are increased by the area 0cbd. Note also that the vertical distance from the marginal profit curve MP_{1+2} to the quota price line r (arrowed) must equal $\beta_1\mu_1$.

Suppose, now, that we have an allocation of non-transferable quotas that is inefficient; *i.e.*, one that differs from the equilibrium allocation under transferable quotas. Consider a non-transferable quota allocation to a vessel which deviates from the efficient allocation by plus or minus $\tilde{Q}$ units. In the case of $p_1 + \mu_1 = \lambda = r$, the vessel's optimal catch would then be expected to alter by $\pm\tilde{Q}/\sum_{j=2}^{n}\beta_j$. Taking two similar vessels, a reallocation of quota between the two vessels away from an efficient allocation should leave the total volume of discards unchanged. However, if at the efficient non-transferable quota allocation the value of μ_1 is close to zero, then we can envisage a $\tilde{Q}$ such that the catch could *reduce* by $\tilde{Q}/\sum_{j=2}^{n}\beta_j$ but not *increase* by $\tilde{Q}/\sum_{j=2}^{n}\beta_j$, since given p_1 it would not be profitable to discard $\tilde{Q}/\sum_{j=2}^{n}\beta_j$ more fish even with an increase in the quota allocation (if μ_1 is close to zero, then marginal profit is nearly equal to p_1 at this point). Such a non-transferable quota allocation, although inefficient, will result in a *reduction* in the total discards due to highgrading. The same result will hold wherever the reallocation of quota away from the efficient allocation increases the number of vessels for which it is physically possible (though not profitable) to discard beyond the point at which $\mu_1 = 0$. In this case, the more inefficient the quota allocation, the greater the overall reduction in discards due to highgrading.

Our conclusions about highgrading with transferable and non-transferable quotas were relatively straightforward to derive in the "well-behaved" case where just one grade of fish is discarded. However, generalising to the case of at least two grades where it is profitable to discard can present difficulties. To see the problem, let p_1 *and* p_2 be lower than the equilibrium quota price established under transferable quotas. Given a *non-transferable* quota allocation of Q^* (the same as the efficient allocation) a rational vessel operator will likely first discard all fish of the lowest-priced grade 1, increasing the catch to $Q^*/[1 - \beta_1]$, before discarding any fish of the slightly more valuable grade 2. Suppose at this point marginal profit is equal to p_2 (which is possible if both p_2 and β_1 are relatively high). It will not now be profitable *at the margin* to discard any fish of grade 2, although if the vessel did so and increased the total catch to $Q \; / \sum_{j=3}^{n} \beta_j$, which is the profit-maximising level of catch under transferable quotas, its *total* profits would increase. If the vessel could perceive this at the outset, it would discard grades 1 and 2 together, although it always appears rational at the margin to discard the lowest-priced grade first. The firm's problem, of course, is that with a non-transferable quota it lacks the incentive signals which under transferable quotas are transmitted via the quota price.

Figure 5 illustrates this graphically for three grades, of which grades 1 and 2 command market prices less than the quota price r. With a non-transferable quota equal to the optimal transferable quota demand Q^*, if the vessel begins to discard only fish of grade 1, it will increase the catch to a level q^0. In order to increase the catch further to the optimum q^*, it would now have to start discarding fish of grade 2, but it will not do this because marginal profit is equal to p_2 at this point. Instead of potential short-run profits 0abc, the vessel only earns profits of 0def. With transferable quotas, the vessel equates MP_3 with the cost of quota for grade 3 only ($r\beta_3$) and earns *gross* profits of 0abc (reduced to abg taking account of the cost of quota).

If, with a non-transferable quota, the discarding condition (13) holds for k grades in the catch, then for each of these grades we can write:

$$p_j \beta_j + \mu_j \beta_j = \lambda \beta_j, \quad j = 1, 2, \quad , k,$$

so that:

$$\lambda = \frac{\sum_{j=1}^{k} p_j \beta_j}{\sum_{j=1}^{k} \beta_j} + \frac{\sum_{j=1}^{k} \mu_j \beta_j}{\sum_{j=1}^{k} \beta_j},$$

which, using equation (14), and with some manipulation, gives the general optimal decision rule for non-transferable quotas:

$$\sum_{j=1}^{n} p_j \beta_j - c'(q) = \frac{\sum_{j=1}^{k} p_j \beta_j}{\sum_{j=1}^{k} \beta_j} + \frac{\sum_{j=k+1}^{n} \beta_j}{\sum_{j=1}^{k} \beta_j} \sum_{j=1}^{k} \mu_j \beta_j. \tag{19}$$

Condition (19) requires that at the quota limit fish of grades 1,…,k are discarded together *in the same proportions in which they appear in the catch*. While the expression appears rather cumbersome, note that equation (14) is returned in the special case of one grade of fish discarded (k = 1). The key problem for the vessel with a non-transferable quota is that the information provided by the quota price is lacking. If at every point the vessel could perceive the shadow price of quota λ, it would produce according to equation (19). Discarding the least valuable grades sequentially, lowest value grade first, which appears rational at the margin once the

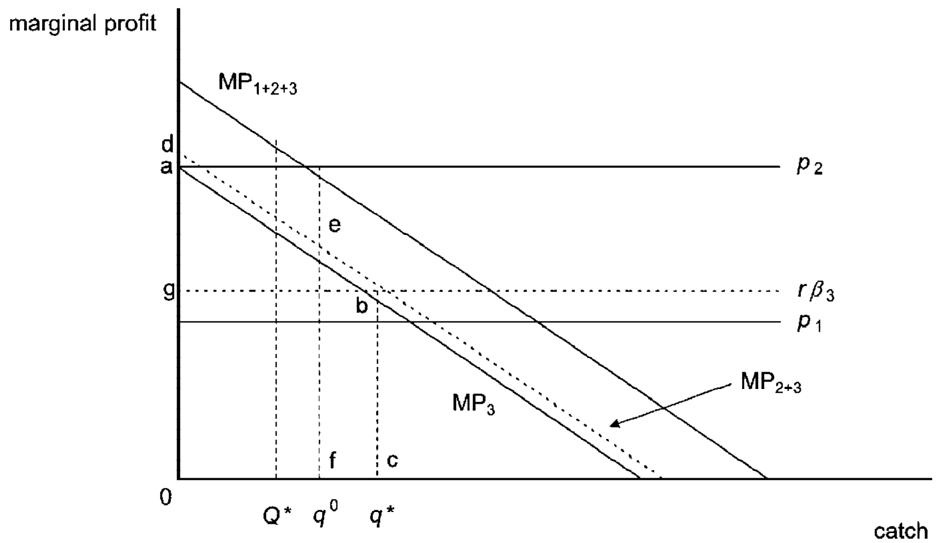

Figure 5. Transferable and Non-transferable Quotas with Three Grades of Fish

quota is filled, may not maximise profits under all conditions. We conclude that in a fishery with many grades of fish, we cannot be sure that for a given individual quota allocation discards due to highgrading will be the same under transferable and non-transferable quotas, even though, all else equal, the *optimal* level of catch *is* the same in each case. It is possible that, under certain conditions, there will be fewer discards with the non-transferable quota allocation.

Highgrading and Quota Price

We know that with transferable quotas the short-run quota price is set equal to marginal profit. But although the discarding behaviour of individual vessels is determined by the quota price, the equilibrium quota price in the fishery is likely to be affected by the discarding behaviour of the fishery as a whole. We can examine this as follows. With a transferable quota, following equation (18) we have, in the case of one grade of fish discarded:

$$\sum_{j=2}^{n} p_j\beta_j - c'(q) = \sum_{j=2}^{n} r\beta_j,$$

or, adding $p_1\beta_1$ to both sides:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q) = \sum_{j=2}^{n} r\beta_j + p_1\beta_1.$$

Now, if $p_1 = r$ so that:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q) = \sum_{j=2}^{n} r\beta_j + p_1\beta_1 = r,$$

then at the margin the vessel will be indifferent between discarding and not discarding fish of grade 1. Given this, the optimal level of catch must be the same whether the vessel discards or not. But if vessels discard, their quota demands will fall. If the quota market is to clear, this implies that the quota price must fall. If the quota price falls, we will have $p_1 > r$ and hence no discarding.

Now, suppose we have $p_1 < r$. With no discarding (assume that all vessel operators chose voluntarily to refrain from discarding),[20] the equilibrium quota price would be given by:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q)\Big|_{q_{nd}} = r_{nd}, \tag{20}$$

where $q_{nd}(=Q_{nd})$ is the optimal catch with no discarding, and r_{nd} is the corresponding quota price. With discarding of all grade 1 fish, we can write:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q)\Big|_{q_d} = \sum_{j=2}^{n} r_d\beta_j + p_1\beta_1, \tag{21}$$

where r_d is the equilibrium quota price with discarding. Since we know that with $p_1 < r$ a vessel is induced to produce where $Q_d < q_d$ (and we know that, if the quota market clears, $Q_d = Q_{nd}$) then given the assumed convexity of the cost function, the LHS of equation (21) is unambiguously smaller than the LHS of equation (20). However, this does not necessarily imply that $r_d < r_{nd}$. In fact, r_d may be lower than, higher than, or the same as r_{nd} and still satisfy equations (20) and (21). For a given set of p_j and β_j, from equations (20) and (21) we have, with a little manipulation:

$$r_{nd} - r_d = \left[c'(q)\Big|_{q_d} - c'(q)\Big|_{q_{nd}}\right] - \beta_1\left[r_d - p_1\right]. \tag{22}$$

We can see that, for a given quota supply, the difference between the quota price with and without discarding depends on the parameters of the cost function, as well as the market value and prevalence in the catch of the lower grade of fish. Note that without such information we cannot even sign the LHS of equation (22). Although, intuitively, we might anticipate a lower quota price with discarding, with a relatively high proportion of fish commanding a relatively low market price, and with relatively high quota prices, it is quite possible that the equilibrium quota price with discarding is the same or even *higher* than if there were no discarding.

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[20] For a discussion of the role of non-monetary influences on compliance with fisheries regulations, see Sutinen and Kuperan (1999) and Hatcher *et al.* (2000).

Conclusions

All else equal and given an *efficient* allocation of quota among vessels, the incentive structure underlying decisions to catch and land fish is essentially the same under transferable and non-transferable quotas. This derives from the equivalence of the shadow price and the quota price, as suggested by Anderson (1994b) and Vestergaard (1996). However, this does not necessarily mean that outcomes will be the same in all cases. Whereas the information provided by the equilibrium short-run quota price in a transferable quota fishery is always available to the vessel, the same is not true of the shadow price of a non-transferable quota. Thus, we saw the possibility that, under certain conditions, a vessel might highgrade less with a non-transferable quota, even though it would be optimal to discard to the same extent as with an identical transferable quota demand. We also saw that the quota price is affected by discarding. In a multispecies transferable quota fishery, discarding of one species with a relatively constrained quota supply will result in a reduction in the quota price for the other species. Highgrading, however, has an ambiguous effect on the quota price. Under certain circumstances, where the total quota supply is relatively small, quota prices are relatively high, and there is a high proportion of low-value grades in the catch, the quota price with highgrading may be *higher* than it would be if vessels did not discard, all else equal.

Where an allocation of non-transferable quotas differs from the efficient allocation, the shadow price of quota deviates from the quota price, which would be established if quotas were transferable. Thus, some vessels will face shadow prices lower than the quota price, while others will face higher shadow prices. While small deviations may leave overall outcomes unaffected, larger deviations will not. The more inefficient the allocation, the greater is the likely reduction in discards due to highgrading under non-transferable quotas compared to transferable quotas. In multispecies fisheries, however, discards due to a mismatch between quotas and catches at the vessel level are likely to be increased with an inefficient allocation of non-transferable quotas.

The overall implications for introducing quota transferability are not clear cut. While highgrading is a potential problem under both non-transferable and transferable quota systems, the inefficient allocation that a non-transferable quota system is likely to produce will tend to minimise discards due to highgrading. In a multispecies fishery, on the other hand, a non-transferable quota system will tend to increase discards due to vessels not holding quota in proportion to the mix of species in the catch. Given this, whether discards overall will increase or decrease in a move from non-transferable to transferable quotas will depend upon the particular characteristics of the fishery and the existing quota management regime.

The results derived in this paper are conditional upon two important assumptions. The first is that enforcement is sufficient to deter landings of over-quota fish, so that incentives to discard depend only upon the shadow price of non-transferable quotas or quota prices in a transferable quota fishery. The second key assumption is that the proportions of different species and grades in the catch are fixed. This disallows both any random variation in the catch composition and, perhaps more importantly, the possibility that the vessel can selectively target particular species or grades of fish.[21]

As Turner (1997) observes, if a vessel has perfect (costless) control over the harvest technology, and, therefore, catch composition, the problem of discarding becomes trivial. In our models, the β_i or β_j would be costless to alter and would simply

[21] Note that these key assumptions are also made, implicitly, in previous studies on discarding.

be set at profit-maximising levels (which would presumably be zero for those species or grades commanding market prices less than the quota or shadow price). There are two more realistic modeling approaches to admitting some control over the catch composition that could profitably be pursued. The first is to assume that changing the harvest technology is a costly investment decision and that, once a decision over the technology is made, the catch composition cannot be altered in the short run. The second is to allow some degree of control over the catch composition in the short run, with implications for short-run costs; *i.e.*, the variable costs of effort. Clearly these two approaches are not mutually exclusive. We could envisage technology investment decisions which then determine the margins over which control can be exercised and the implications for variable costs. It would be interesting then to explore the conditions under which discarding ceases to be profitable; *i.e.*, where it is profit maximising to land the catch in its entirety. This issue is left for further investigation.

The other interesting question deserving further investigation is whether, under certain circumstances, it might be socially optimal to relax enforcement and allow some margin of over-quota landings. From the conditions for discarding, it can be seen that there must be a tradeoff between compliance with quotas at the landing site and incentives to discard. To the extent that both discarding and landing over-quota fish impose a social cost, and given that enforcement is costly, there may be a social optimum that does not require perfect control over landings.[22] If the stock externalities resulting from excessive catches affect only future outcomes, then by ignoring these in the short run, over-quota landings *and* discarding could be socially optimal given the set TAC. In a dynamic setting, whether or not firms' private decisions to cheat or to discard are socially optimal will then depend to a large extent on whether the TAC is set at the right level (assuming the current TAC is costly to increase only in the sense that doing so reduces the future value of the fishery).

References

Anderson, L.G. 1989. Enforcement Issues in Selecting Fisheries Management Policy. *Marine Resource Economics* 6:261–77.

___. 1991. A Note on Market Power in ITQ Fisheries. *Journal of Environmental Economics and Management* 21:291–96.

___. 1994a. A Note on the Economics of Discards. *Marine Resource Economics* 9:183–86.

___. 1994b. An Economic Analysis of Highgrading in ITQ Fisheries Regulation Programs. *Marine Resource Economics* 9:209–26.

Anderson, L.G., and D.R. Lee. 1986. Optimal Governing Instrument, Operation Level and Enforcement in Natural Resource Regulation: The Case of the Fishery. *American Journal of Agricultural Economics* 68:678–90.

Arnason, R. 1990. Minimum Information Management in Fisheries. *Canadian Journal of Economics* 23:630–53.

___. 1994. On Catch Discarding in Fisheries. *Marine Resource Economics* 9:189–207.

Becker, G.S. 1968. Crime and Punishment: An Economic Approach. *Journal of Political Economy* 86:169–217.

Boyce, J.R. 1996. An Economic Analysis of the Fisheries Bycatch Problem. *Journal of Environmental Economics and Management* 31:314–36.

[22] This possibility has been shown for more general fishery models without discarding (*e.g.*, Sutinen and Andersen 1985).

Charles, A.T., R.L. Mazany, and M.L. Cross. 1999. The Economics of Illegal Fishing: A Behavioural Model. *Marine Resource Economics* 14:95–110.

Clark, C.W. 1985. *Bioeconomic Modelling And Fisheries Management.* New York, NY: Wiley.

___. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, 2nd Edition. New York, NY: Wiley.

Copes, P. 1976. A Critical Review of the Individual Quota as a Device in Fisheries Management. *Land Economics* 62:278–91.

Grafton, R.Q. 1995. Rent Capture in a Rights-based Fishery. *Journal of Environmental Economics and Management* 28:48–67.

Hatcher, A., S. Jaffry, O. Thébaud, and E. Bennett. 2000. Normative and Social Influences Affecting Compliance with Fishery Regulations. *Land Economics* 76:448–61.

Hatcher, A., S. Pascoe, R. Arnason, and R. Banks. 2002. *Future Options for UK Fish Quota Management*. Report to the UK Department for the Environment, Food and Rural Affairs. CEMARE Report No 58. Portsmouth, UK: University of Portsmouth.

Hatcher, A., and A. Read. 2001. The Allocation of Fishing Rights in UK Fisheries. *Case Studies on the Allocation of Transferable Quota Rights in Fisheries*, R. Shotton, ed., pp. 1–14. FAO Fisheries Technical Paper 411. Rome: FAO.

Keeler, A. 1991. Noncompliant Firms in Transferable Discharge Permit Markets: Some Extensions. *Journal of Environmental Economics and Management* 21:180–89.

Kirkley, J.E., and I.E. Strand. 1988. The Technology and Management of Multispecies Fisheries. *Applied Economics* 20:1279–92.

Malik, A. 1990. Markets for Pollution Control when Firms are Noncompliant. *Journal of Environmental Economics and Management* 18:97–106.

Milliman, S.R. 1986. Optimal Fishery Management in the Presence of Illegal Activity. *Journal of Environmental Economics and Management* 13:363–87.

Neary, J.P., and K. Roberts. 1980. The Theory of Household Behaviour under Rationing. *European Economic Review* 13:25–42.

Shavell, S. 1992. A Note on Marginal Deterrence. *International Review of Law and Economics* 12:345–55.

Squires, D. 1987. Public Regulation and the Structure of Production in Multiproduct Industries: An Application to the New England Otter Trawl Industry. *RAND Journal of Economics* 18:232–47.

Squires, D., H. Campbell, S. Cunningham, C. Dewees, R.Q. Grafton, S.F. Herrick, J. Kirkley, S. Pascoe, K. Salvanes, B. Shallard, B. Turris, and N. Vestergaard. 1998. Individual Transferable Quotas in Multispecies Fisheries. *Marine Policy* 22:135–59.

Sutinen, J.G., and P. Andersen. 1985. The Economics of Fishery Law Enforcement. *Land Economics* 61:387–97.

Sutinen, J.G., and K. Kuperan. 1999. A Socio-Economic Theory of Regulatory Compliance. *International Journal of Social Economics* 26:174–93.

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

Vestergaard, N. 1996. Discard Behaviour, Highgrading and Regulation: The Case of the Greenland Shrimp Fishery. *Marine Resource Economics* 11:247–66.

Appendix A

Lagrange functions and first-order (Kuhn-Tucker) conditions for maximising solutions to the objective functions shown in the text:

1. Multispecies fishery with $i = 1,2,\ldots,m$ non-transferable species quotas:

$$L = \sum_{i=1}^{m} p_i\left[\beta_i q - d_i\right] - c(q) - \sum_{i=1}^{m} \lambda_i\left[\beta_i q - d_i - Q_i\right] - \sum_{i=1}^{m} \mu_i\left[d_i - \beta_i q\right] \qquad \text{(A-1)}$$

$$L_q = \sum_{i=1}^{m} p_i\beta_i - c'(q) + \sum_{i=1}^{m} \mu_i\beta_i - \sum_{i=1}^{m} \lambda_i\beta_i \le 0, \quad q \ge 0, \quad L_q q = 0$$

$$L_{d_i} = -p_i + \lambda_i - \mu_i \le 0, \quad d_i \ge 0, \quad L_{d_i} d_i = 0$$

$$L_{\lambda_i} = -\beta_i q + d_i + Q_i \ge 0, \quad \lambda_i \ge 0, \quad L_{\lambda_i}\lambda_i = 0$$

$$L_{\mu_i} = -d_i + \beta_i q \ge 0, \quad \mu_i \ge 0, \quad L_{\mu_i}\mu_i = 0$$

2. Multispecies fishery with $i = 1,2,\ldots,m$ transferable species quotas:

$$L = \sum_{i=1}^{m} p_i\left[\beta_i q - d_i\right] - c(q) - \sum_{i=1}^{m} r_i Q_i - \sum_{i=1}^{m} \lambda_i\left[\beta_i q - d_i - Q_i\right] - \sum_{i=1}^{m} \mu_i\left[d_i - \beta_i q\right] \qquad \text{(A-2)}$$

$$L_q = \sum_{i=1}^{m} p_i\beta_i - c'(q) + \sum_{i=1}^{m} \mu_i\beta_i - \sum_{i=1}^{m} \lambda_i\beta_i \le 0, \quad q \ge 0, \quad L_q q = 0$$

$$L_{d_i} = -p_i + \lambda_i - \mu_i \le 0, \quad d_i \ge 0, \quad L_{d_i} d_i = 0$$

$$L_{Q_i} = -r_i + \lambda_i \le 0, \quad Q_i \ge 0, \quad L_{Q_i} Q_i = 0$$

$$L_{\lambda_i} = -\beta_i q + d_i + Q_i \ge 0, \quad \lambda_i \ge 0, \quad L_{\lambda_i}\lambda_i = 0$$

$$L_{\mu_i} = -d_i + \beta_i q \ge 0, \quad \mu_i \ge 0, \quad L_{\mu_i}\mu_i = 0$$

3. Non-transferable species quota with $j = 1,2,\ldots,n$ grades of fish:

$$L = \sum_{j=1}^{n} p_j\left[\beta_j q - d_j\right] - c(q) - \lambda\left\{\sum_{j=1}^{n}\left[\beta_j q - d_j\right] - Q\right\} - \sum_{j=1}^{n} \mu_j\left[d_j - \beta_j q\right] \qquad \text{(A-3)}$$

$$L_q = \sum_{j=1}^{n} p_j\beta_j - c'(q) + \sum_{j=1}^{n} \mu_j\beta_j - \lambda \le 0, \quad q \ge 0, \quad L_q q = 0$$

$$L_{d_j} = -p_j + \lambda - \mu_j \le 0, \quad d_j \ge 0, \quad L_{d_j} d_j = 0$$

$$L_{\lambda} = -\sum_{j=1}^{n}\left[\beta_j q - d_j\right] + Q \ge 0, \quad \lambda \ge 0, \quad L_{\lambda}\lambda = 0$$

$$L_{\mu_j} = -d_j + \beta_j q \ge 0, \quad \mu_j \ge 0, \quad L_{\mu_j}\mu_j = 0$$

4. Transferable species quota with j = 1,2,…,n grades of fish:

$$L = \sum_{j=1}^{n} p_j\left[\beta_j q - d_j\right] - c(q) - rQ - \lambda\left\{\sum_{j=1}^{n}\left[\beta_j q - d_j\right] - Q\right\} - \sum_{j=1}^{n}\mu_j\left[d_j - \beta_j q\right] \quad \text{(A-4)}$$

$$L_q = \sum_{j=1}^{n} p_j\beta_j - c'(q) + \sum_{j=1}^{n}\mu_j\beta_j - \lambda \le 0, \quad q \ge 0, \quad L_q q = 0$$

$$L_{d_j} = -p_j + \lambda - \mu_j \le 0, \quad d_j \ge 0, \quad L_{d_j} d_j = 0$$

$$L_Q = -r + \lambda \le 0, \quad Q \ge 0, \quad L_Q Q = 0$$

$$L_\lambda = -\sum_{j=1}^{n}\left[\beta_j q - d_j\right] + Q \ge 0, \quad \lambda \ge 0, \quad L_\lambda \lambda = 0$$

$$L_{\mu_j} = -d_j + \beta_j q \ge 0, \quad \mu_j \ge 0, \quad L_{\mu_j}\mu_j = 0$$

Appendix B

Proof of the equivalence of incentives under a non-transferable quota and an equal transferable quota demand.

To begin, take equation (14) and write this condition as:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q)\Big|_{q_{nt}} = p_1 + \left[1 - \beta_1\right]\mu_1, \quad \text{(B-1)}$$

where p_1 is the market price of the grade of fish, which it is profitable to discard in order to increase the catch by one unit while remaining within the quota limit, and q_{nt} is the optimum level of catch with a non-transferable quota. Recall that μ_1 is zero unless the discard constraint is binding, in which case there are no more fish of this grade left to discard so catch cannot be increased to the point where marginal profit equals p_1. With a transferable quota, following equation (18) we have, in the case of one grade of fish discarded:

$$\sum_{j=2}^{n} p_j\beta_j - c'(q)\Big|_{q_t} = \sum_{j=2}^{n} r\beta_j, \quad \text{(B-2)}$$

where q_t is the optimal level of catch. Now we can add $p_1\beta_1$ to both sides of (B-2) to get:

$$\sum_{j=1}^{n} p_j\beta_j - c'(q)\Big|_{q_t} = \sum_{j=2}^{n} r\beta_j + p_1\beta_1, \quad \text{(B-3)}$$

which we can compare directly with equation (B-1) and observe that, for a given set of p_j and β_j, we have:

$$\sum_{j=2}^{n} r\beta_j + p_1\beta_1 = p_1 + [1 - \beta_1]\,\mu_1 + \left[c'(q)\big|_{q_{nt}} - c'(q)\big|_{q_t}\right],$$

which rearranges to:

$$r = p_1 + \mu_1 + \frac{1}{[1 - \beta_1]}\left[c'(q)\big|_{q_{nt}} - c'(q)\big|_{q_t}\right]. \qquad \text{(B-4)}$$

If $p_1 < r$, then the RHS of equation (B-4) has a value greater than p_1. Given this, $\mu_1 = 0$ would imply a higher optimal level of catch with a non-transferable quota, given the assumed convexity of the cost function, but if $\mu_1 > 0$ the optimal level of catch with a non-transferable quota could be higher, lower, or the same as the optimal level of catch with a transferable quota. However, if we have a non-transferable quota allocation that is *exactly* the same as the efficient quota allocation, Q^*; *i.e.*, the equilibrium transferable quota demand, we would expect the optimal level of catch to be the same in each case; *i.e.*, $q_{nt} = q_t$ (*given* Q^*, if profits are maximised with a constant quota cost, r, for every unit of fish landed, they should also be maximised under equivalent conditions, but where that cost is not incurred). If the optimal level of catch is the same, equation (B-4) collapses to:

$$r = p_1 + \mu_1, \qquad \text{(B-5)}$$

with $\mu_1 > 0$. Thus, given the same quota allocation, *all* low-value fish are discarded in each case, and the volume of discards will equal $q^* - Q^*$, where $q = Q / \sum_{j=2}^{n}\beta_j$. If this were not true, then with the non-transferable quota we would either have: *not* all fish of the low-value grade discarded at $q_{nt} = q_t$, in which case we must have $\mu_1 = 0$, which from equation (B-4) requires $q_{nt} > q_t$, or *all* fish of the low-value grade discarded at $q_{nt} < q_t$, which cannot be the case given Q^* and β_1. Thus, we can affirm that if from equation (13) we have $p_1 + \mu_1 = \lambda$ and from equation (16) $r = \lambda$, then the shadow price of the non-transferable quota is equal to the transferable quota price.