

Discard Behavior, Highgrading and Regulation: The Case of the Greenland Shrimp Fishery

NIELS VESTERGAARD

Danish Institute of Fisheries Economics Research

Abstract *A formal economic analysis of the discarding problem is presented, focusing on the individual fisherman and the effect of different regulations on the fisherman's incentives to discard. It is shown that in a nonregulated fishery, either multispecies or single species/multisize, where the only constraints are the hold capacity and the length of the season, the fisherman may have rational incentives to discard/highgrade, if the marginal trip profit of an extra fishing day is greater than the average trip profit. Regulation by TAC does not change the incentives to discard. However, under INTQs and ITQs, the incentives to discard increase. The incentives to discard decrease under ITQs compared to INTQs, if the unit quota price is smaller than the shadow price of the quota. The model is applied to the Greenland shrimp fishery, where it demonstrates the reported discard behavior in the fishery. Finally, different regulations of discard are applied and discussed in the model. The analysis suggests that regulation of fishing days could be a promising alternative to usual suggested measures like tax/subsidies and landings obligations.*

Key words Discard, Greenland, highgrading, incentives, INTQs, ITQs, shrimp.

Introduction

Discarding of fish with positive social value is a result of the disconnection between the behavior of the fishers and the incentives produced by the managers.¹ Discards are also due to incomplete structured property rights (e.g., open access or even ITQs) which are a property right to a resource flow but not the resource stock itself. In these cases the management does not provide incentives to the fishers which induce behavior in accordance with a socially optimal fishery. However, the management agency often indirectly accepts discards which could be the result of a regulation with the purpose to reduce the short-run net economic benefit of the fishery. The alternative could be an uncontrolled growth of fishing effort with even more economic waste than the discards (EEC Commission 1992).

Reports of discards of valuable species are numerous (Lehmann and Degel 1991; EEC commission 1992; Huppert *et al.* 1992) and the discards occur under several different regulatory frameworks. The discard problem has been discussed in the literature mainly with reference to regulation by Individual Transferable Quotas (ITQs) (Copes 1986) with the exceptions of Arnason (1994), Anderson (1994), and Clark (1985).

Niels Vestergaard is associate professor at the Danish Institute of Fisheries Economics Research, South Jutland University Centre, Niels Bohrs Vej 9, DK-6700 Esbjerg, Denmark; e-mail: nv@suc.suc.dk.

I am grateful for the helpful reviews and advice provided by Tove Christensen and Dale Squires. Constructive comments by two anonymous referees have also improved the paper. The author remains responsible for any remaining errors.

¹ Another example is the use of effort well beyond the efficient level.

Discards may be induced by regulation, but from an economic point of view, discarding is efficient in cases where the marginal costs of discarding are less than the marginal benefits of discarding (Arnason 1994). In this case the economic waste of not discarding is greater than the waste of discarding.²

The specific regulation of discarding differs from country to country. In Danish fisheries landings of species below the minimum landing size and landings beyond the allowed quotas are not permitted. The fishermen have, in both cases, the choice to either discard or land the catch illegally. Regulation of mesh size has an indirect effect on discarding through the influence on the size distribution of the catch.

In Norway only discards of viable species are allowed; dead or dying species must be landed. However, it is not permitted to catch fish below a given minimum landing size and to catch illegal bycatches. Therefore, if the fishery is conducted in an area where small size fish or bycatches are over-represented, the fishery must stop and the vessel has to move to another area. The discard ban was mainly imposed to prevent discarding of fish larger than the minimum landing size. In the Greenland shrimp fishery the catch of shrimps greater than 2 grams must be landed, *i.e.*, discarding is only allowed of shrimps smaller than 2 grams.

The purpose of this paper is to address the discard problem from an economic point of view and to evaluate the incentives of the individual fisher to discard under different regulatory frameworks. The paper focuses on discarding of valuable species, which may be illegal or legal. The model does not include the enforcement issue, so the approach is partial. The paper addresses the incentives to discard and not necessarily the actual level of discarding.

It is shown that in a nonregulated fishery, either multispecies or single species/multisize, where the only constraints are the hold capacity and the length of the season, the fisher may have rational incentives to discard/highgrade if the marginal trip profit of an extra fishing day is greater than average trip profit. An important result obtained shows that changes in the price of the discarded species/size categories influence the incentives to discard more than changes in the landed species/size categories. Regulation by TAC does not change the incentives to discard. However, under Individual Non-Transferable Quotas (INTQs) and ITQs, the incentives to discard increase. Under ITQs the incentives to discard decrease compared to INTQs if the unit quota price is smaller than the shadow price of the quota. The analysis suggests that regulation of fishing days could be a promising alternative to the usual suggested measures such as taxes/subsidies and landings obligations.

The paper is organized as follows. The next section contains some basic considerations. Then a discard model for an individual vessel is formulated. The model is solved for an nonregulated fishery and the conditions for profitable discarding is found. The model is also solved subject to different regulation systems. The Greenland shrimp fishery was chosen for the study, because they have had INTQs and now have ITQs implemented. The model is applied to the Greenland shrimp fishery and different instruments to reduce discard are applied in the model. The paper closes with discussion and conclusions.

Basic Considerations

Discarding of fish requires that the fishery operates with different grades (Arnason 1994). It can be a single species fishery with size divided catches, or a multispecies

² Discarding may be efficient from the viewpoint of private firms, but inefficient from the perspective of society, especially over time due to lost growth and reproduction.

fishery, where the species receive different prices, or a combination of both. The division of catch into different grades is a result of either regulation (*e.g.*, minimum landing size) or different economic grades, *i.e.*, different purpose and/or value or a combination of both.

Three different types of constraints may influence the level of discards. First, there are economic constraints. Species with no market value are usually discarded at sea, and species with a positive market value may be discarded if the costs of handling, storage, and landing exceed the market value. Second, there are legal constraints, which include minimum landing size, bycatch rules, and quotas. Legal constraints tend to increase discarding, *e.g.*, when the catch of a valuable bycatch species is above the allowed quantity. Third, there are technical constraints. Examples of technical constraints are hold and sorting capacity, and durability of the catch before turning it into a product that can be stored in the hold. For a given trip the hold capacity can induce highgrading, *i.e.*, discarding of low value sizes/species to make room for high value sizes/species. In a given fishery several of the constraints are usually present at the same time. For example, the Danish mixed fishery for human consumption in the North Sea contains elements of all three types of constraints.

The model in the next section is relatively simple with respect to these constraints. At the outset, there is only one technical constraint, the hold capacity. In a later section different legal constraints representing the regulatory framework are added. It is shown that even in this simple model discarding can be profitable.

The Model

In order to explain the rationality of discarding valuable species, the focus must be the individual fisher. The model must describe how fishers will operate in a specific fishery. It is assumed that fishers maximize profit one season at a time and that fishers decide on the number of trips N ,³ the length of each trip E ,⁴ and the discard per trip D_j of size category j to maximize profit for the season, see equation (1). The annual fixed cost can be disregarded, given the short time period considered. The model is formulated here as a single species model with different sizes but can also be interpreted as a multispecies model. The model can be seen as an extension of the models by Clark (1985) and Anderson (1994).

The individual fisher's maximizing problem for one season is:

$$\begin{aligned} \max_{N, E, D_j} \Pi &= N\pi(E, D_j) \\ &= N \left\{ \sum_{j=1}^J [p_j(a_j y E - D_j) - c_l(a_j y E - D_j) - c_d D_j] - CE(E) \right\} \end{aligned} \quad (1)$$

Subject to

$$N(E + E_0) \leq T \quad (2)$$

³ Assume that the parameters remain constant throughout the year (i is an index of the trip number), *i.e.*, $y_i = y$ and $a_{ij} = a_j$ all the trips will be of equal length, $E_i = E$, and the discard per trip, $d_{ij} = d_j$, is equal as well.

⁴ The implicit assumption in mathematical programming models is that the production technology is separable, *i.e.*, inputs (and outputs) can be combined to a single composite input, normally represented by fishing days, see Squires, Alauddin, and Kirkley (1994) and Anderson (1994).

$$a_j y E - D_j \geq 0 \quad j = 1, \dots, J \quad (3)$$

$$\sum_{j=1}^J (a_j y E - D_j) \leq K \quad (4)$$

$$N, E, D_j \geq 0 \quad j = 1, \dots, J \quad (5)$$

The trip profit, $\pi(E, d_j)$ in equation (1), consists of four parts. The first part is the revenue, $\sum_{j=1}^J [p_j(a_j y E - D_j)]$. The total catch per trip is catch per unit effort y , which is assumed constant throughout the year, times effort per trip E . The landings of each size category j is the total catch times the size distribution a_j less the discard D_j . Revenue is given by landings multiplied by the market prices, p_j . The market prices are assumed exogenously given at the vessel level and hence constant.

The next three terms of the trip profit is the trip cost. Following Arnason (1994) this cost is divided into three parts: landing cost, discarding cost, and effort or harvesting cost.⁵ In traditional fisheries models, the landing and discarding cost are normally ignored. The landing cost is cost connected to retaining (and if necessary processing) the catch and landing it, see Arnason (1994). The landing cost, the second part of the trip profit, $cl_j(a_j y E - D_j)$, is assumed to be proportional with the landings of each grade, *i.e.*, cl_j is the variable cost of landing one unit of catch. Anderson (1994) does not include landing cost. The third part of the trip profit is the discarding cost, $c_d D_j$. It is assumed that the marginal discarding cost is constant and independent of size categories, *i.e.*, c_d is the variable cost of discarding one unit of catch. The fourth part of the trip profit is the cost of effort, $CE(E)$, with $CE' > 0$ and $CE'' > 0$. Further it is assumed that the fixed trip cost is positive, *i.e.*, $CE(0) > 0$.⁶ This means that there are costs depending on the number of trips.

The first constraint (2), the season constraint, limits the length of the season to T . Hence the number of trips multiplied by the trip length (including steaming and harbor time E_0 between two trips) must be less than the length of the season. If this season constraint holds with equality, then the objective is to maximize the profit per trip-day, *i.e.*, the average trip profit. The second constraint (3), the landing constraint, restricts the landings of each size category to be nonnegative (discards of each grade cannot exceed the catch of each grade). The third constraint (4), the hold constraint, requires the total landings per trip to be less than or equal to the hold capacity (K) of the vessel. Finally, the constraints in equation (5) restrict the variables to be non-negative.

This problem is so far without any kind of regulation. If, for example, a total allowable catch (TAC) is introduced in the model, the length of the season T will be further limited. Individual quotas may also be analyzed in this model, while analysis of regulation by mesh size, closed areas, and other technical measures requires a more detailed model with respect to the biological specification.

Solution of the Model

The number of trips N is an integer. However the solution is found without restricting N to be an integer to provide more insight into solutions close to the optimal solution. This approach is recommended in Zions (1974), when the value of the inte-

⁵ A reviewer suggested that the division of cost into three parts imposes strong restrictions on the substitution possibilities in the production technology.

⁶ The fixed trip cost are, for example, costs of administration and fixed wages.

ger is expected to be somewhat larger than 1. Numerical simulations can be used to find the optimal integer value afterwards.⁷

The Lagrange-function of the problem reads:

$$L = N \left\{ \sum_{j=1}^J [p_j(a_j y E - D_j) - c_l_j(a_j y E - D_j) - c_d D_j] - CE(E) \right\} \\ + \lambda_1 [T - N(E + E_0)] + \sum_{j=1}^J \lambda_{2j} (a_j y E - D_j) + \lambda_3 [K - \sum_{j=1}^J (a_j y E - D_j)]. \quad (6)$$

The first order conditions are:

$$\frac{\partial L}{\partial N} = \sum_{j=1}^J [p_j(a_j y E - D_j) - c_l_j(a_j y E - D_j) - c_d D_j] - CE(E) - \lambda_1(E + E_0) \leq 0 \quad (7)$$

$$N \frac{\partial L}{\partial N} = 0 \quad (8)$$

$$\frac{\partial L}{\partial E} = N \left[\sum_{j=1}^J (p_j a_j y - c_l_j a_j y) - CE'(E) \right] - \lambda_1 N + \sum_{j=1}^J \lambda_{2j} a_j y - \lambda_3 \sum_{j=1}^J a_j y \leq 0 \quad (9)$$

$$E \frac{\partial L}{\partial E} = 0 \quad (10)$$

$$\frac{\partial L}{\partial D_j} = -N(p_j - c_l_j + c_d) - \lambda_{2j} + \lambda_3 \leq 0 \quad j = 1, \dots, J \quad (11)$$

$$D_j \frac{\partial L}{\partial D_j} = 0 \quad j = 1, \dots, J \quad (12)$$

$$\lambda_1, \lambda_{2j}, \lambda_3 \geq 0 \quad j = 1, \dots, J \quad (13)$$

From equation (11) it is seen that the discard level of size j is positive if the marginal cost of discarding, which is $c_d + p_j$, is smaller than the marginal benefit of discarding c_l_j . This requires at least that $p_j - c_l_j < 0$, *i.e.*, the marginal cost related to retain and land the catch is larger than the market price. If $p_j - c_l_j > 0$, then discarding might be profitable if the hold constraint (4) is binding, *i.e.*, $\lambda_3 > 0$. It will be shown in the next section that a binding hold constraint is only a necessary condition for discarding, not a sufficient condition. Net market prices np_j for size j can without any loss of generality be defined as $np_j = p_j - c_l_j$. It is assumed in the following that $np_j > 0$. The size categories are ordered relatively to the net market price, *i.e.*, $np_1 < np_2 < \dots < np_j < \dots < np_J$.

For a given trip length it is relatively easy to determine the optimal discard level. Discarding is a costly activity. Therefore, for a given trip length, the highest

⁷ Of course pathological examples can be constructed, where the optimal integer solution is not close to the optimal non-integer solution.

possible value of the catch is obtained by retaining the whole catch if the hold constraint is not binding, see appendix. If the hold constraint is binding, only the necessary amount should be discarded. It is optimal first to discard the cheapest size, *i.e.*, size 1.

In order to determine the solution, each of the possible cases where the inequality constraints (2)-(5) are binding or not binding have to be examined. Since there are $2 + J + 2 + J$ constraints there will be $2^{2+J+2+J}$ configurations possible at the optimum. Because the purpose here is to investigate the solution where discarding is profitable, the number of cases to examine is much fewer.

Assume that profit is positive, *i.e.*, $N > 0$ and $E > 0$ and equations (7) and (9) hold with equality. When the season constraint (2) is binding, the corresponding shadow price λ_1 can be obtained from equation (7):

$$\lambda_1 = \frac{\sum_{j=1}^J [np_j(a_j y E - D_j) - c_d D_j] - CE(E)}{E + E_0} \quad (14)$$

The right-hand-side of equation (14) is the average trip profit (*ATP*), which is positive. Therefore at the optimum, the season constraint will be binding. Substituting equation (14) into first order condition (9) gives:

$$N \left[\sum_{j=1}^J np_j a_j y - CE'(E) \right] - N \frac{\sum_{j=1}^J [np_j(a_j y E - D_j) - c_d D_j] - CE(E)}{E + E_0} \quad (15)$$

$$+ \sum_{j=1}^J \lambda_{2j} a_j y - \lambda_3 \sum_{j=1}^J a_j y = 0$$

This equation together with equation (11) forms the basis for analyzing a number of cases depending on which constraints are binding for the fishing activity. In the appendix the different cases are analyzed.⁸ Here we will concentrate on the cases where discarding of size-category just becomes profitable, *i.e.*, two cases: (i) $D_1 > 0$ and the landing constraint (3) is nonbinding; and (ii) $D_1 > 0$ and the landing constraint is binding.

Conditions for Profitable Discarding

If discarding of size category 1 is optimal, then equation (11) holds as an equality. The solution where discarding of size 1 is optimal can then be found by solving equation (15) for λ_3 and substituting the expression into equation (11) for $j = 1$ to give an expression for the decision to discard:

$$\sum_{j=1}^J np_j a_j y - CE'(E) - (np_1 + c_d)y \quad (16)$$

$$\frac{\sum_{j=1}^J np_j a_j y E - CE(E)}{E + E_0} - \frac{(np_1 + c_d)D_1}{E + E_0} + \frac{1}{N} (1 - a_1) \lambda_{21} y$$

The left-hand-side of equation (16) represents the marginal trip profit (*MTP*), $\sum_{j=1}^J np_j a_j y - CE'(E)$ and the costs of discarding one day's catch (*DC*₁), $(np_1 + c_d)y$.

⁸ There are 2^{1+J+J} configuration possibilities left.

An extra fishing day yields MTP , but in order to make room for the catch, size 1 is discarded at the costs of foregone net revenue (np_1), and discarding cost (c_d), of one day's catch, y . The two first terms on the right-hand-side show ATP . The last term on the right-hand-side is the shadow value of size 1 to discard expressed in terms of one day's catch of landed size categories. Discarding (of size category 1) is optimal if $MTP - DC_1 > ATP(D_1 = 0)$. Discarding continues until $MTP - DC_1 = ATP(D_1 > 0)$, *i.e.*, equation (16) is obtained. This corresponds to maximum of ATP . If the landing constraint (3) becomes binding such that further discarding of size 1 is not possible, then $\lambda_{21} > 0$.

Discarding is optimal if marginal benefits (MTP) are greater than marginal costs, the latter consisting of discarding cost (DC_1) plus average trip profit (ATP). The average trip profit is the opportunity cost of a day, time cost, because the season is limited. If as assumed in Anderson (1994) the goal was to maximize the trip profit (*i.e.*, no season limit) then the trip will continue until $MTP - DC_1 = 0$ or the discard constraint is binding, and consequently a trip will last longer in the model of Anderson.

In figure 1 the trip profit is shown as a function of the trip length. If the trip length is less than E_1 , where the hold capacity is binding, then there is no discarding. If the trip length is between E_1 and E_2 then size 1 is discarded. If the trip length is between E_2 and E_3 then size 2 is also discarded. In general, if the trip length is between E_k and E_{k+1} , then size k is discarded. The optimal trip length E^* is found where the average trip profit is maximized.

Further insight into conditions for profitable discarding is possible when equation (16) is manipulated to show the total marginal cost of replacing a unit of size 1 with a unit of the landed size categories:

$$\frac{\sum_{j=2}^J a_j np_j}{1 - a_1} - np_1 = \frac{1}{(1 - a_1)y} [CE'(E) + ATP(D_1 \geq 0) + c_d y] + \frac{1}{N} \lambda_{21} \quad (17)$$

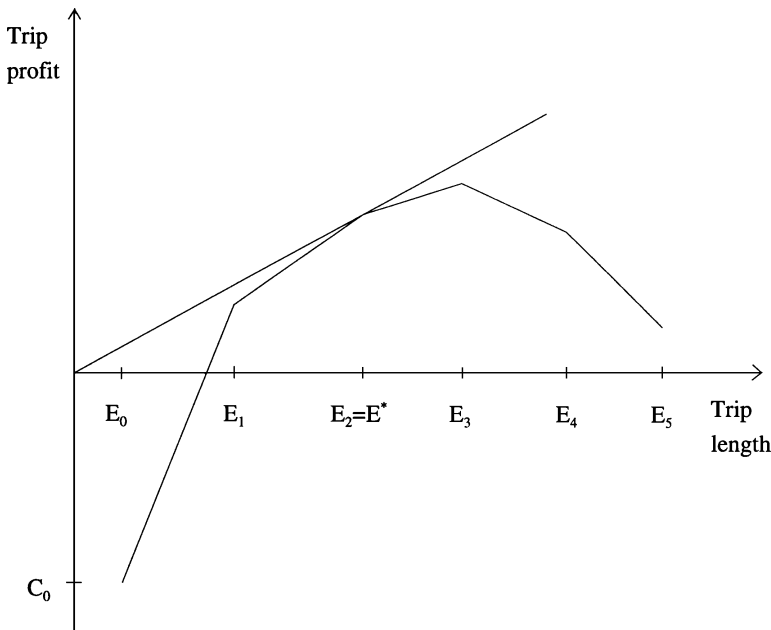


Figure 1. Optimal Trip Length

The left-hand-side of equation (17) expresses the benefit of replacing a unit of size 1 with a weighted unit of the landed size categories. The cost of highgrading are captured in the brackets on the right-hand-side of equation (17) and involve, expressed in units of producing an extra unit of landed size categories: (i) the marginal effort cost, (ii) the average trip profit (*i.e.*, the time cost), and (iii) the marginal cost of discarding. In Huppert, Anderson, and Harding (1992) and Anderson (1994) only the first and the third parts of the costs are mentioned. Equation (17) says that discarding is optimal when the difference between the average net price of the landed size categories and the net price of the discarded size category compensates for the cost of discarding.

As Anderson (1994) points out, price-differences and a binding hold constraint are not enough to induce discarding. The price-difference has to be sufficiently large to compensate for the costs, see equation (17). Discarding can be profitable even if the net market price is positive. If the prices used in the model reflect social value, and hold capacity is costly, then the conclusions also remain in force from a social point of view (Anderson 1994).

Neither equation (16) nor (17) explicitly expresses the discard level, but instead the incentives to discard are expressed. If the left-hand-side increases (decreases) then the incentives to discard increase (decrease), while if the right-hand-side increases (decreases) then the incentives to discard decrease (increase). The incentives are expressed on a trip level.

The incentives to discard expressed in equation (17) depend on E_0 , y , ATP , CE' , a_j , c_d , and p_j . From equation (17) the following conclusions can be made:

1. If the steaming time E_0 increases, then the incentives to discard increase. The average trip profit then decreases and then the fishing time, E , or λ_{21} must increase as the right-hand-side still has to be equal to the constant left-hand-side. In figure 1 the trip profit curve moves to the right, when E_0 increases, leading to longer trips.

From equation (17) it can be shown that the shorter the steaming time, the less the price of the landed size categories will influence the incentives. At the limit, with no steaming time, equation (17) reduces to:

$$c_d + np_1 = \frac{E}{yE - D_1} \left[\frac{CE}{E} - CE'(E) - \frac{1}{N} \lambda_{21}(1 - a_1)y \right] \quad (18)$$

This result is different from the result of Anderson (1994). The incentives to discard depends not on the price *difference*, but on the price *level* of the discarded size.

2. If the share of size category 1, a_1 , increases, then the incentives to discard decrease.
3. Because the firm operates where the average effort cost (AEC) is greater than or equal to the marginal effort cost (MEC), the main difference between AEC and MEC is the fixed trip cost $CE(0)$. A rise in fixed trip cost and AEC (*i.e.*, ATP decreases) increases the incentives to discard. In figure 1 the trip profit curve moves downward as fixed trip cost increases.
4. The price of size category 1, p_1 , influences the incentives to discard more than the weighted price of the other size categories. To see this, in figure 2 the profit curve in the middle shows the initial situation with E_2 as the optimal trip length. If the price of the discarded size 1 increases, then MTP increases, but the DC_1

increases as well. Therefore the profit curve will break more at E_1 than before. In figure 2, E_1 becomes the optimal trip length. If the prices of other sizes decrease then the slope of the profit curve becomes less steep for every E . In figure 2 the optimal trip length is unchanged, *i.e.*, E_2 . This information can be utilized when discard management is designed. In equation (17) only the expression on the left-hand-side will change with changes in the price of the discarded size 1, while corresponding changes in the weighted price of the landed size categories change both the expression on the left-hand-side and the term with the time cost on the right-hand-side in the same direction.

Regulation

In this section the effects on the discard behavior of three different regulation systems are analyzed and compared. The three systems are total allowable catch (TAC), individual non-transferable quotas (INTQs) and individual transferable quotas (ITQs). There are several reasons for this choice. The three regulation systems are distinct systems. Secondly, they often represent the evolution of the management system in many fisheries from open access, over TAC and restricted access, to individual quotas. Arnason (1994) and Anderson (1994) analyzed the discard problem under open access and ITQs. It is relevant, however, to compare INTQs with ITQs, because in some fisheries where ITQs have been introduced there have been restrictions on the transferability or thin ITQs markets, which *de facto* change the ITQs to INTQs [see Squires, Kirkley, and Tisdell (1995) for an overview].

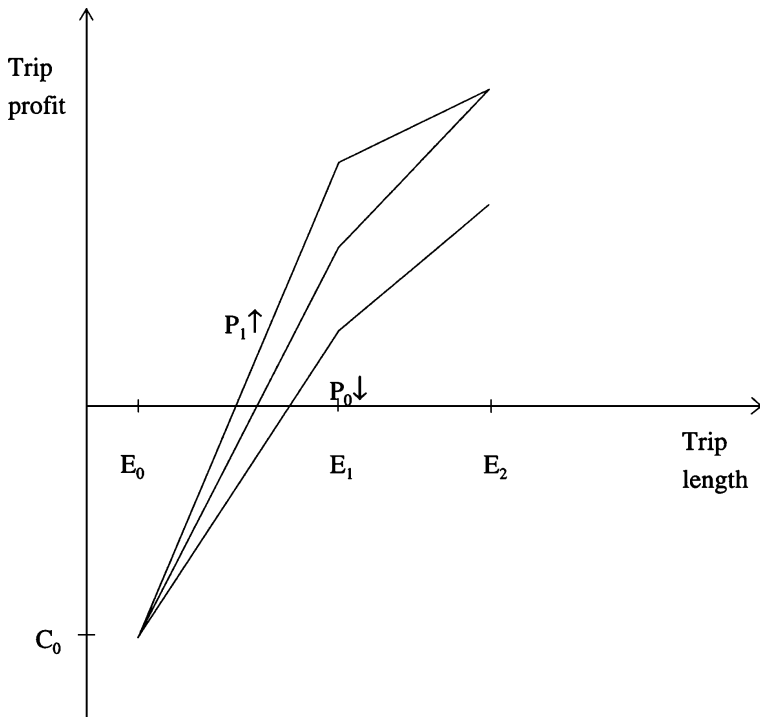


Figure 2. Effect of Changes in Prices

Total Allowable Catch

Regulation by TAC can be introduced into the model by reducing the length of the season T . If TAC is supposed to reduce the total (reported) catch, then the fishery will close before the end of a normal season. As the length of the season is not included in the conditions (7)-(11), the discard behavior remains unchanged. But the total discard (and the total catch) per vessel will decline as the number of trips fall. This is a short-run consideration, however. Over time, as a possible positive profit attracts new fishers, the season becomes even shorter which may lead to decreasing CPUE. The result is that the incentives to discard decrease.

Individual Nontransferable Quotas

The system of INTQs allocates to each fishing unit a catch quota, which limits the harvest (or landings) within the season.

INTQs can be introduced in the model (1)-(5) by including the condition that total landings must be smaller than or equal to the quota \mathbf{Q} , *i.e.*, the quota constraint:

$$N \left[\sum_{j=1}^J (a_j y E - D_j) \right] \leq \mathbf{Q} \quad (19)$$

The first order conditions are then:

$$\begin{aligned} \frac{\partial L}{\partial N} &= \sum_{j=1}^J [np_j(a_j y E - D_j) - c_d d_j] \\ &- CE(E) - \lambda_1(E + E_0) - \lambda_4 \sum_{j=1}^J (a_j y E - D_j) \leq 0 \end{aligned} \quad (20)$$

$$N \frac{\partial L}{\partial N} = 0 \quad (21)$$

$$\begin{aligned} \frac{\partial L}{\partial E} &= N \left[\sum_{j=1}^J np_j a_j y - CE'(E) \right] \\ &- \lambda_1 N + \sum_{j=1}^J \lambda_{2j} a_j y - \lambda_3 \sum_{j=1}^J a_j y - \lambda_4 N \sum_{j=1}^J a_j y \leq 0 \end{aligned} \quad (22)$$

$$E \frac{\partial L}{\partial E} = 0 \quad (23)$$

$$\frac{\partial L}{\partial D_j} = -N(np_j + c_d) - \lambda_{2j} + \lambda_3 + \lambda_4 N \leq 0 \quad j = 1, \dots, J \quad (24)$$

$$D_j \frac{\partial L}{\partial D_j} = 0 \quad (25)$$

$$\lambda_1, \lambda_{2j}, \lambda_3, \lambda_4 \geq 0 \quad (26)$$

Assume as before that profit is positive, *i.e.*, equations (20) and (22) hold with equality. For a given trip length E , it is more complicated to determine the discard due to the interaction between N and D_j in the quota constraint (19). The general point here is that if both the quota and the season constraints are binding, then increased discarding for a given trip length will lead to a nonbinding quota constraint, because N , due to the season constraint cannot increase. Consequently further increases in discarding are nonoptimal.

If the quota constraint is not binding, then the solution is the same as before. It is therefore assumed in the following analysis that the quota constraint (19) is binding, *i.e.*, $\lambda_4 > 0$.

Introduction of INTQs in a Situation Where Discarding was Unprofitable

In this section and the next it is considered whether introducing INTQs changes the incentives to discard compared to situations without regulation, where it is either optimal to land the entire catch or optimal to discard some of the catch. The analysis takes place in two steps. In the first step, the trip length is fixed and it is investigated whether it is optimal to discard. In the second step, we see whether it is optimal to change the trip length.

Introducing a quota and keeping the trip length fixed implies that the season constraint (2) becomes nonbinding $\lambda_1 = 0$, because the number of trips must fall due to a binding quota constraint (by assumption). Solving equation (20) for λ_4 and inserting in equation (24) for $j = 1$ gives that discarding is optimal if:

$$\frac{\sum_{j=1}^J np_j a_j y E - CE(E)}{\sum_{j=1}^J a_j y E} > np_1 + c_d \quad (27)$$

Equation (27) simply says that if the average profit per unit fish, which is the benefit of one unit of landed fish, is greater than the total marginal discarding cost of one unit of size 1 fish, then discarding is optimal. Hence even when the hold constraint is nonbinding, it can be optimal to discard. It has been argued (Anon. 1993) that highgrading under individual quotas is due to limited hold capacity, but this is not necessarily the case.

If discarding is optimal then it continues to increase until either the season constraint is binding or one of the discard constraints is binding and it is not profitable to continue with the next size. When discarding increases, the number of trips can be raised (however limited by the quota constraint), because the landings per trip decrease. But the discard and hence the number of trips can only be increased to a certain limit determined by the season constraint.

If equation (27) does not hold, then it depends on the hold constraint whether it is optimal to change the trip length. If the hold constraint is nonbinding then the optimal trip length is reduced slightly.⁹ If the hold constraint is binding and $MTP - (np_1 + c_d)y > 0$ ¹⁰ then it is optimal to extend the trip and start discarding.

If equation (27) is fulfilled, then the optimal trip length can decrease or increase, but discarding will still be optimal.

The incentives to discard are, compared to the nonregulated case, increased.

⁹ From equation (22) the optimal trip length is found where $MTP = ATP$ of fishing days. In the nonregulated case the optimality condition was $MTP = ATP$ of trip days. ATP of fishing days is lesser than ATP of trip days, so MTP has to be bigger than before and therefore the optimal trip length is reduced.

¹⁰ Solve equation (22) for λ_3 and insert in equation (24).

Introduction of INTQ in a Situation where Discarding was Profitable

Introduction of a binding quota in this situation results in increasing discarding, if profit per landed unit is greater than total marginal discarding costs of the relevant size j . Discarding stops increasing when either one of the discard constraints becomes binding and it is unprofitable to continue with the next size or the season constraint becomes binding. The optimal trip length will increase in these cases.¹¹

If it is nonoptimal to increase the discard, then the hold constraint is still binding (now together with the quota constraint). In this case, it is optimal to increase the trip length and hence the discarding, if MTP is greater than the costs of discarding one day's catch of the relevant sizes; otherwise the trip length remains the same.

As before, compared to the nonregulated case, the incentives to discard are increased.

In the further analysis, the situation is relevant where the hold, season, and quota constraints are binding. If all three constraints are binding, then substituting λ_1 [from equation (20)] and λ_3 [from equation (22)] into equation (24) for $j = 1$ gives the following expression:

$$\sum_{j=1}^J np_j a_j y - CE(E) - (np_1 + c_d)y - \frac{\sum_{j=1}^J [np_j (a_j y E - D_j) - c_d D_j] - CE(E)}{E + E_0} \quad (28)$$

$$+ \lambda_4 \frac{\sum_{j=1}^J (a_j y E - D_j)}{E + E_0} - \frac{1}{N} [\lambda_{21}(1 - a_1)y - \sum_{j=2}^J \lambda_{2j} a_j y] \leq 0.$$

If some discarding is optimal, then equation (28) holds as an equality. If equation (28) is compared to the situation without any regulation [equation (16)], the fifth term in equation (28) (the term with λ_4) makes the difference. The trip lasts longer and increases the incentives to discard compared to the nonregulated case.

Individual Transferable Quotas

If it is possible to trade quota,¹² then the quota constraint (19) and the objective function (1) change. The quota constraint has to take into account that quota units can be sold and bought and can be written:

$$N \left[\sum_{j=1}^J (a_j y E - D_j) \right] \leq Q \quad (29)$$

where, Q is the amount of quota units after trading has occurred. The quota units are non-negative:

$$Q \geq 0 \quad (30)$$

The objective function changes to:

¹¹ The hold constraint becomes nonbinding. Therefore, not the whole catch of one fishing day has to be discarded, which reduces the costs of discarding and the optimal trip length increases.

¹² As we look only at one year, the quota trade is annual lease.

$$\max_{N, E, D_j, Q} \Pi = N\pi(E, D_j) = N\left\{\sum_{j=1}^J [np_j(a_j yE - D_j) - c_d D_j] - CE(E)\right\} - s(Q - \mathbf{Q}) \quad (31)$$

where, s is the price per quota unit.

The problem now consists of equations (2)-(5) and equations (29)-(31). The first order conditions are equations (20)-(26) and:

$$\frac{\partial L}{\partial q} = -s + \lambda_4 \leq 0 \quad (32)$$

$$q \frac{\partial L}{\partial q} = 0 \quad (33)$$

If $q > 0$, then equation (32) says that in optimum the price per unit quota s is equal to the shadow price of the quota constraint λ_4 . Hence if the quota price is lower than the shadow price under INTQs, $s < \lambda_4$, then it is optimal to buy quotas. If the season constraint (2) is binding, then a larger part of the total season catch is landed with a larger quota and the discard falls. If the season constraint is nonbinding, then the number of trips increases with a larger quota which may lead to a binding season constraint and consequently lower trip length and discard share. If the season constraint does not bind, the discard share remains unchanged. This implies that the incentives to discard are lower than in the INTQ system. If the quota price is larger than the shadow price under INTQs, then it is optimal to sell quotas, thereby increasing the incentive to discard.

Compared to TAC/no-regulation the ITQ system will increase the incentives to discard if the price per unit quota is positive. This increase in discarding incentives follows from the analysis of INTQs [see equation (28)] because every binding quota (*i.e.*, positive shadow price) will increase the incentives to discard. This result is different than the result found in Anderson (1994). Anderson found that introduction of an ITQ system in a situation where highgrading was not profitable will only induce highgrading, if $s > p_1 + c_d$.

In summary, it is not possible to conclude that ITQs will increase the discard; instead it depends critically on which management system it replaces.

The Greenland Shrimp Fishery

The shrimp fishery on offshore fishing grounds in the Davis Strait started around 1970.¹³ In 1976 the annual catch reached a level of about 40,000 tonnes and in the 1990s catch over 50,000 tonnes are seen. The participating fleet is multinational. The main part of the catch is taken by vessels from Greenland (87.1% in 1991) and Canada (11.8%), but vessels from France, Denmark, and the Faroe Islands also participate in the fishery. The offshore fleet of Greenland consists of three types of vessels. A major part of the fishing fleet consists of factory trawlers with processing plants on board. As a part of the license conditions, one group of these factory trawlers is allowed to process 75% to 90% of the catch on board, whereas a second group is allowed to process 30% to 50% of the catch only. For both groups, the remaining catch must be landed to the factories on shore. The third group of vessels participat-

¹³ This section is based on Christensen and Vestergaard (1993).

ing in the offshore fishery is formed by minor boats with no processing plants on board and no licences to process. The entire catch of this part of the fishing fleet must be landed to the factories on shore.

Three main products of shrimp are produced. Frozen, unpeeled shrimps which can be raw or cooked are produced at the processing plants at sea. At the processing industry on shore, the shrimps are cooked and peeled. Besides the product type, the sales prices also depend on the size of the shrimp. The commercial fleet commonly operates with five size categories: count¹⁴ 50-70, count 70-90, count 90-120, count 120-150, and count 150+.

From 1984 to 1991 the offshore shrimp fishery of Greenland was regulated by an individual non-transferable quota (INTQ) system. In 1991 the Greenland Home Rule¹⁵ implemented an individual transferable quota (ITQ) system.

According to an observer program, two kinds of discard take place on shrimp factory trawlers (Lehmann and Degel 1991). Shrimp is discarded partly due to low quality (quality discard) and partly due to inferior size (size discard), in order to highgrade the catch. The amount of quality discard is low compared to the size discard. Carlsson and Kannevorff's (1992) observation program found that the size discard in the Greenland fleets consists of shrimps less than 8.5 grams, *i.e.*, less than count 120. The extent of the discard of the Greenland factory trawlers has been estimated based on the information from the observation program, to be about 25% of the reported catch. Christensen and Vestergaard (1993) estimate the total discard in 1991 to be about 23%.

The regulation of discards is based on command and control. A catch of shrimp larger than 2 grams must be landed, *i.e.*, discard of shrimp smaller than 2 grams is allowed. It is very difficult to control whether the discard regulation is respected and a perfect control requires personnel on every vessel, which is an expensive solution. Instead the Greenland Home Rule controls the vessels by means of spot checks.

Model Results from the Case of Greenland Shrimp Fishery

The basic input parameters are determined from account information from three factory trawlers, see also Christensen and Vestergaard (1993). The costs are divided into landing, discard, and effort cost: (i) landing cost depending on the extent of processing, the retained catch are mainly wages, processing, handling, and sales; (ii) effort cost depending on the days at sea are mainly fuel, gear, and maintenance; and (iii) effort cost depending on the number of trips (*i.e.*, fixed trip costs) which are mainly administration, travel, fuel for steaming, and maintenance.

The landing cost is deducted from the sales prices in order to obtain net market prices. In order to obtain increasing marginal effort costs a quadratic effort cost equation is used:

$$CE(E) = c_1 \cdot E^2 + c_2 \cdot E + c_0$$

where c_0 is the fixed trip costs. The input parameters used in the model are shown in table 1.

Table 2 reports the results from running the model with the three different regulatory systems. The baseline run (*i.e.*, nonregulated fishery) of the model shows that it is optimal to discard the cheapest size category, but not to the full extent. Even with-

¹⁴ Count is defined as number of shrimps per kilogram.

¹⁵ The sub-national government of Greenland.

Table 1. Input Parameters

Size Group	a_j	p_j (DKK)
1	0.280	3.81
2	0.257	6.34
3	0.254	15.27
4	0.184	27.01
5	0.025	80.12
c_0 : 1,083,457 E_0 : 3 days K : 300,000 kg	c_1 : 21,000 y : 10,000 kg/fishing day T : 176 days	c_2 : 100 Q : 900,000 kg

Table 2. Results

	Nonregulated	INTQ	ITQ	
			$s = 2$	$s = 4.4$
Profit (1,000 DKK)	12,094	11,239	11,526	11,351
Catch (tonnes)	1,632	1,670	1,642	1,682
Discard (tonnes)	354	770	460	903
Landings (tonnes)	1,278	900	1,182	779
Trip length	41	59	44	68
Shadowprice of quota (DKK)		3.3	2	4.4

out any kind of regulation, discarding can be optimal. Sensitivity analysis of fixed trip costs, steaming and harbor time, catch per unit effort, and hold capacity gives the expected results. This analysis also shows that the result is relatively robust, *i.e.*, large changes in the parameters are necessary to change the discard behavior.

Introducing a binding quota constraint (*i.e.*, INTQs) in the model increases the discard compared to the previous analysis as expected. Size category 2 is also discarded. The catch level is the same as in the baseline run. The trip length is expanded and the number of trips declines. The shadow price of quota is 3.3 DKK. This result fits the observed discard behavior in the fishery under INTQs (Lehmann and Degel 1991; Carlsson and Kannevorff 1992).

Under ITQs the discard decreases when the quota price is lower than the shadow price of quota, because it is optimal to buy more quota and with binding season constraint the share of the catch that is discarded must fall. If, for example, the quota unit price is 2 DKK, then quota units are bought and the discard level decreases. It consists now only of size category 1. Compared to the baseline run the amount of discard is higher. The opposite result is obtained when the quota price is higher than the shadow price. For example, with a quota unit price at 4.4 DKK the discard increases, such that size categories 1 and 2 are now discarded to the full extent.

In all cases the catch is at the same level because the season is utilized completely. The difference is how the catch is divided into landings and discard.

Regulation of Discards

Specific regulation of discards with the purpose of eliminating or reducing discarding can be based on landing obligations, taxes/subsidies, or length of the season. The analysis of these measures is provided within the case of the shrimp fishery.

Landing Obligations

Landing obligations of size categories that are usually discarded can be implemented by setting a fixed share of the total landings or quota, which has to consist of the usually discarded size categories at least. The problem with this instrument is that the share of these size categories varies from vessel to vessel, from area to area, and over the season, which makes a proper setting of the share almost impossible (Anderson 1994). A practical policy could be to set an uniform share, but the question is whether such a policy can reduce the incentives to discard.

In the nonregulated fishery a landing obligation of a share of the catch beyond the catch share of the potential discarded sizes 1 and 2 will eliminate the discard of sizes 1 and 2, but discarding of size 3 is necessary in order to provide the required share of sizes 1 and 2. Anderson (1994) called this situation lowgrading. Setting a share of the catch under the discard share will reduce, but not eliminate, the discard. A landing obligation will reduce the trip length and hence the number of trips and the landings will increase.

In the quota-based fishery the fixed share is implemented as in Anderson (1994), so that only a certain share of the quota is allowed to consist of the potential not-discarded size categories. Then it is up to the fishermen to decide whether to discard or land the potential discarded sizes.

Under INTQs, setting a proper fixed share of the quota is more difficult. The problem is that the vessel owner maximizes the value of the part of the quota which is without landing obligation. This can lead to discards of size categories that were previously landed. This applies to both shares above and under the discard share. Therefore this regulation can be forced to be extended to other size categories than scheduled, which can lead to reactions from the fishers and in the end undermine the purpose of the regulation. However, introduction of a landing obligation will lead to reduction or the same level in catch, discard, and trip length, because now possible discarding costs more. The profit will fall. But if the discards and catch fall, there is room for increasing the individual quota up to a point, where the catch is the same as before.¹⁶ This will compensate the fishers to some extent.

The situation under ITQs compared to INTQs is in principle the same as before, *i.e.*, without landing obligations. If the shadow price of quota is greater than the quota price, then it is optimal to buy quota, and therefore the discard share is on the same level or smaller than under INTQs. If the required landed share of the quota that has to be landed is higher than the catch share, then in some cases (not too high quota price) it is optimal to buy quota beyond landings to meet the landing obligation. Anderson (1994) also treats this situation, but does it independent of the quota price. If it is optimal to sell quota, then the discard share is at the same level or, larger than under INTQs.

In general the shadow price of quota is higher under landings obligations than without landings obligations. Therefore ITQs with landings obligation will, all things equal, reduce the incentives to discard compared to ITQs without landings obligations. However implementation of landing obligations in an ITQ fishery may distort the quota market and influence the number of successful quota trades negatively.

Taxes/Subsidies

It was shown that changes in the prices of the discarded size categories influence the incentives to discard more than changes in prices of the retained size categories. The

¹⁶ It is assumed that the discard is included in the assessment of the stock and hence in the TAC, which is the base when setting individual quotas.

cause is the season constraint. Therefore the main problem is to find a subsidy level for the discarded size categories that will eliminate the incentives to discard. If a budget-neutral regulation is required, then taxing the retained size categories is a relatively easy task, because this will only influence the incentives to discard in a limited extent. Obviously taxing and/or subsidizing too hard can induce discards of higher valued size categories, *i.e.*, lowgrading.

For example, in the nonregulated case of the shrimp fishery, the discard is eliminated by raising the price of size 1 by 2 DKK and decreasing the prices of the other sizes so that the regulation is budget-neutral. In the INTQ case the situation is more complicated. The season constraint is binding, but reducing the discards requires that the trip length decreases and hence the season constraint becomes nonbinding. This changes the conditions for highgrading such that the prices of the retained size categories are influenced with the same factor as the discarded sizes. Therefore it is the price differences that matters if the season constraint is nonbinding.

In our model of the shrimp fishery the discard level can be reduced to contain only the low valued sizes by raising the prices on size 2 and decreasing the prices of 4 and 5 corresponding so the budget neutrality is obtained. In the model it is possible to find subsidy levels and tax levels that will lead to elimination of the discard. Under ITQs, if the quota price is lower than the shadow price of quota obtained from running the model under INTQs, then raising the price of sizes 1 and 2 and decreasing the prices of 4 and 5 correspondingly can eliminate the discard. But as before the proper levels of subsidies and taxes depend on the quota price. Higher quota-prices means higher levels of subsidies and taxes. It can be a relatively difficult task to keep the right levels of subsidies/taxes in a situation with fluctuations in the quota prices.

Effort Regulation

Instead of introducing landings obligations or subsidy/tax, where extensive and costly information and control is necessary, then simply reducing the length of the season may be an alternative. The analysis of ITQs and INTQs in the Greenland shrimp fishery shows that if the length of the season was reduced, then the discards could be reduced to the discard level in the nonregulated case. However input controls can distort the composition of factor inputs and lead to higher cost. Therefore in a proper cost/benefit analysis of management of discard, the change in control costs, in discard levels, and in the flexibility in planning of the fishing operations must be considered.

Reducing the length of the season by one-quarter in the model reduces the discard level by reducing the number of trips under ITQs, while under INTQs the discard level is reduced, because the trip length is reduced.

If the catch-composition in some periods consists of more low-valued size categories, then the fishery in these periods could be closed instead of simply shortening the season. Hereby low valued categories (often small and young individuals) are protected and the discard level in general is reduced through a shorter season.

Discussion and Conclusions

In a simple model, where fishers decide the number of trips and trip length over the season, this paper show that incentives to discard can exist. The only constraints in the model are the length of season and size of hold. Incentives to discard require the price-difference between discarded and non-discarded fish to be greater than the

costs of replacing the discard, which consists of the discarding cost, effort cost and time cost. It was also shown that the price of discarded fish influences the incentives more than the price of the retained fish.

Introduction of different regulations into the fishery may change the incentives to discard. Under TAC, where the fishery closes when the total quota is landed, the incentives to discard do not change. The discarded amount and the catch per boat may decrease, however, because the number of trips decreases.

Under INTQs it was shown that discard per trip increases compared to the TAC/nonregulated fishery, if the average trip profit per landed unit is larger than the total marginal cost of discarding individuals of the size in question. If the average trip profit per landed unit is less than the cost, then discard will also increase if marginal trip profit per fishing day is larger than the cost of discarding one day's catch of fish of the size in question. Otherwise the discard is unchanged. In sum, the incentives to discard in INTQ fisheries are larger than the incentives to discard in TAC/nonregulated fisheries.

Whether ITQs compared to INTQs lead to increased incentives to discard depends on the quota price. If the quota price is larger than the shadow price of quota from INTQs, then it is optimal to sell quota. If it is not optimal to sell the entire quota and stop fishing, then the incentives to discard are increased. If the quota price is less than the shadow price, then it is optimal to buy quota and hence the incentives to discard decrease. Therefore compared to INTQs the incentives to discard under ITQs can either fall or increase. If the incentives in ITQ fisheries are compared with the incentives in TAC/nonregulated fisheries, the incentives are increased.

The model is applied to the Greenland Shrimp Fishery in the Davis Strait. Discarding can be optimal even in the nonregulated fishery and the model confirms the observations made on the discard behavior in INTQ fisheries. Under ITQs the incentives to discard will decrease if the quota price is less than 3.3 DKK.

Three different management measures regarding discard are applied in the model: taxes and subsidies, landings obligations, and effort regulation. The observation on the different influence of the prices of different sizes can be used to design proper levels of taxes and subsidies. It is concluded that limiting the number of fishing days per season in INTQ or ITQ fisheries may be a promising alternative to the traditional measures, because it is much easier to control fishing days than catch and landings of different grades/species. Furthermore, relatively detailed information of catch composition is needed when designing levels of taxes or landings shares. However, regulating the number of fishing days reduces the flexibility of the fishermen. This loss has to be compared with the benefit of reducing the discard.

References

- Anon. 1993. The Use of Individual Quotas in Fisheries Management. *OECD Documents Paris*.
- Anderson, L.G. 1994. An Economic Analysis of Highgrading in ITQ Fisheries Regulation Programs. *Marine Resource Economics* 9(3):209–26.
- Arnason, R. 1994. On Catch Discarding in Fisheries. *Marine Resource Economics* 9(3):189–207.
- Carlsson, C.M., and P. Kanneworff. 1992. Estimate of Shrimp Discard from Shrimp Factory Trawlers in Davis Strait and Denmark Strait in 1991. *NAFO SCR Doc.* 92/56.
- Christensen, S., and N. Vestergaard. 1993. A Bioeconomic Analysis of the Greenland Shrimp Fishery in the Davis Strait. *Marine Resource Economics* 8(4):345–65.
- Clark, C.W. 1985. *Bioeconomic Modelling and Fisheries Management*. New York: John Wiley & Sons.

- Copes, P. 1986. A Critical Review of the Individual Quota as a Device in Fisheries Management. *Land Economics* 62(3):278–91.
- EEC Commission. 1991. *Report 1991 from the Commission to the Council and the Parliament about the Common Fishery*. Sec(91):2288.
- Huppert, D.D., L.G. Anderson, and R. Harding. 1992. Consideration of the Potential Use of Individual Transferable Quotas in the North Pacific Groundfish Trawl Fishery. Vol 2. *National ITQ Study Report*. National Oceanic and Atmospheric Administration (NOAA).
- Lehmann, K., and H. Degel. 1991. An Estimate of Shrimp Discard from Shrimp Factory Trawlers in Davis Strait and Denmark Strait. *NAFO SCR Doc.* 91/40.
- Squires, D., M. Alauddin, and J. Kirkley. 1994. Individual Transferable Quota Markets and Investment Decisions in the Fixed Gear Sablefish Industry. *Journal of Environmental Economics and Management* 27:1985–204.
- Squires, D., J. Kirkley, and C.A. Tisdell. 1995. Individual Transferable Quotas as a Fisheries Management Tool. *Reviews in Fisheries Science* 3(2):141–69.
- Zionts, S. 1974. *Linear and Integer Programming*. New Jersey: Prentice Hall.

Appendix

Solution of the Model (No Regulation)

Hold Constraint (4) is Not Binding, $\lambda_3 = 0$

From equation (11) it follows that $D_j = 0$ and $\lambda_{2j} = 0$. Equation (15) can then be formulated as:

$$\sum_{j=1}^J np_j a_j y - CE'(E) = \frac{\sum_{j=1}^J np_j a_j y E - CE(E)}{E + E_0} \quad (\text{A1})$$

The left-hand-side of equation (A1) is the marginal trip profit (*MTP*) and the right-hand-side is *ATP*. The trip continues until *MTP* is equal to *ATP*. If the decision was to maximize the trip profit, then the trip will continue until *MTP* = 0, *i.e.*, the trip last longer. But if the season is limited, the extension of the trip reduces the profit which could be obtained on other trips within the season.

To determine the length of a trip (*E*) and the number of trips (*N*), solve equation (A1) for *E* and then from equation (2) *N* can be found.

The Hold Constraint is Binding, $\lambda_3 > 0$

Several cases are possible here. In order to simplify the problem, it is assumed that there are three size categories ($J = 3$) of fish. If the optimal discard level is positive, it will consist of category 1 and 2, with 1 as the primary category.¹⁷ It is inoptimal to discard the highest valued category, *i.e.*, $D_3 = 0$ and $\lambda_{23} = 0$. For a given trip length *E* the discard level of D_1 and D_2 can be found from equation (4).

Condition for No Discard. If no discarding takes place, then $D_1, D_2, \lambda_{21},$ and $\lambda_{22} = 0$. From equation (11) the following expression can be obtained:

$$\lambda_3 \leq N(np_1 + c_d) \quad (\text{A2})$$

¹⁷ It is optimal to discard first the cheapest size (p_1).

Insert λ_3 from equation (A2) into equation (15):

$$\sum_{j=1}^3 np_j a_j y - CE'(E) - (np_1 + c_d)y \leq \frac{\sum_{j=1}^3 np_j a_j y E - CE(E)}{E + E_0} \quad (\text{A3})$$

The left-hand-side of equation (A3) shows the marginal trip profit (*MTP*) and the loss from discarding the catch of one fishing day (DC_1). The right-hand-side shows the average trip profit (*ATP*). The trip continues until the hold constraint becomes binding, where $MTP + DC_1 < ATP(D_1 = 0)$. It is optimal to land the whole catch and the number of fishing days can be determined from equation (4) as K/y .

Conditions for Discard of Size Category 1. Here equation (11) holds with equality for $j = 1$. If equation (11) is solve for λ_3 and substituted into equation (15), we get:

$$\begin{aligned} \sum_{j=1}^3 np_j a_j y - CE'(E) - (np_1 + c_d)y &= \frac{\sum_{j=1}^3 np_j a_j y E - CE(E)}{E + E_0} \\ &- \frac{(np_1 + c_d)D_1}{E + E_0} + \frac{1}{N}(1 - a_1)\lambda_{21}y \end{aligned} \quad (\text{A4})$$

The left-hand-side of (A4) shows the marginal trip profit when discarding size category 1. The right-hand-side shows the average trip profit which now consists of *ATP* with no discarding and the average discarding costs. When the hold constraint becomes binding then discarding of size category 1 is optimal if $MTP + DC_1 > ATP(D_1 = 0)$. Discarding continues until $MTP + DC_1 = ATP(D_1 > 0)$. If the discard constraint (3) becomes binding, then $\lambda_{21} > 0$ in order to obtain equal-sign in equation (A4).

If $\lambda_{21} = 0$, then from equation (4) D_1 is to be expressed as a function of E and equation (A4) can be solved for E . If $\lambda_{21} > 0$, then from equation (3) D_1 is expressed as a function of E and from equation (4) E can be found.¹⁸

Discard of Size Category 2. If discarding of size category 2 is optimal, then equation (11) holds with equal-sign for $j = 1$ and 2, and eliminating λ_3 from these equations gives an expression for λ_{21} :

$$\lambda_{21} = \lambda_{22} + N(np_2 - np_1) \quad (\text{A5})$$

Equation (A5) inserted into equation (A4) yields:

$$np_3 - np_2 = \frac{1}{a_3 y} [CE'(E) + ATP(D_1, D_2 > 0) + c_d y] + \frac{1}{N} \lambda_{22} \quad (\text{A6})$$

If discarding of size category 2 is optimal, then the price difference between size-category 3 and 2 is greater than or equal to the costs expressed in the brackets on the right-hand-side of equation (A6).

¹⁸ Then from equation (A4) λ_{21} can be found.