ABARE CONFERENCE PAPER 94.4

High-grading in fisheries managed using individual catch quotas

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38th Annual Conference of the
Australian Agricultural Economics Society
Wellington, New Zealand, 8–10 February 1994

High-grading is the practice of discarding low priced fish while at sea in order to raise the average value of a catch. The non-reporting of catch can have serious consequences for fisheries that are managed using individual catch quotas set to prevent over fishing. In this paper, a simple model is used to give necessary and sufficient conditions for high-grading to take place. The impact of price changes and changes to the size of the catch quota on the level of high-grading is also analysed. Finally, the model is applied to the Australian Northern Prawn fishery to determine the extent of possible high-grading if individual catch quotas are introduced.

ABARE project 50.006

1. Introduction

One way to reduce the problem of over fishing in a common property fishery is to introduce individual catch quotas that limit the total weight of fish that may be caught in a season by each operator[1]. In Australia, the Southern Bluefin Tuna fishery and the south east fishery are Commonwealth fisheries managed using individual transferable quotas. In addition, several state managed fisheries operate under ITQ systems.

The effectiveness of catch quotas depends on the ability of authorities to monitor individual catch levels. However, difficulties in measuring true catch levels arise because catch is usually weighed on shore[2]. This gives operators the opportunity to under report their catch by discarding some part of it while undetected at sea. In particular, it may profit some operators to increase the average unit price of their catch by discarding low priced fish over the course of a season. The non-reporting of the discarded fish allows operators to catch above quota during the season but still meet quota requirements as measured on shore. This practice is known as high-grading.

Non-reporting of true catch levels because of high-grading has a number of serious implications for the management of a fishery (Baulch and Pascoe 1992). For example, the understanding of stock dynamics for most species is based, in part, on the interpretation of catch and effort data. Incorrect data, resulting from the under reporting of catch, may lead to overestimation of sustainable harvest levels, depending on the stock assessment technique being used. In turn, the total catch quota, set in order to meet the economic and biological objectives of a fishery's management program, may be too high. This can lead to a rapid and more than optimal depletion of fish stocks. One further implication of high-grading is that it gives operators some flexibility in adjusting catch levels, even when catch quotas are in place. As a result, catch levels could change following shifts in economic variables. This means, for example, that price changes may need to be taken into account when setting catch quotas to meet biological objectives.

Issues relating to the enforcement of regulations in fisheries have been considered in some detail (see Anderson 1987 and Anderson 1989 for a survey of the issues). However, the specific question of high-grading does not appear to have been addressed in the modelling

1 The potential problem of overfishing in common property fisheries is investigated by Pitcher and Hart (1982). The potential improvements in efficiency from the introduction of catch quotas (and particularly transferable quotas) are discussed by Campbell (1984).

2 Anderson (1989) notes that the costs associated with monitoring catch levels at sea can be significantly higher than those associated with monitoring on shore.

of commercial fishing behaviour. The objective in this paper is to analyse the economic incentives facing a representative operator in a fishery that is managed using individual catch quotas and where high-grading cannot be detected.

The paper is organised as follows. In the next section a simple model of fishing behaviour when high-grading is a possibility is developed. In section 3, the necessary and sufficient conditions for high-grading to take place are derived and marginal conditions that give the optimal level of high-grading are obtained. In sections 4 and 5 these marginal conditions are used to obtain formulae that give the responsiveness of catch to changes in fish prices and the catch quota. In section 6, formulae that give the level of an operator's profit from fishing in the presence of high-grading are provided. An empirical application of the results is presented in section 7. In the final section, implications of the restrictive assumptions of the model are outlined and implications of the results for fisheries management are considered.

2. The model

The model presented here is based on a number of simplifying assumptions that abstract from issues that may have an impact on levels of high-grading. Two important assumptions in this research are that operators catch a single species and that they are unable to target different proportions of grades of fish once the season begins. Also, behaviour is modelled as if all fishing and high-grading takes place over a single period. However, this assumption can be relaxed to incorporate multiple fishing trips and changes to the composition of fish grades in total catch over time.

A more significant simplification is that operators face full certainty about future prices and changes to the fish population and catch over the course of the season. Possible implications of this assumption are considered briefly in section 7.

Prices and grade

The market price of fish is denoted by the real valued variable P. By definition, it is taken that higher grades of fish attract higher values of P.

Fishing technology

A representative profit maximising fisherman owns a fishing technology, assumed to be fixed at the start of the season. The technology is described fully by:

means of misreporting catch. Hence, the possibility that fish might be landed illegally, for example, is not considered here.

Catch constraints

An individual quota is allocated preventing the operator from bringing more than $\overline{Q}$ tonnes of fish to shore during the season. The type of quota considered here applies indiscriminately across all grades. Separate quotas for different types or grades of fish are not considered here. Further, it is assumed that additional quota cannot be purchased and by implication quota overruns are not permitted.

While the catch quota might be imposed in order to constrain the true total catch Q, in practice it can limit only the observed or reported catch (Q.F($\hat{P}$). The true total catch exceeds the reported catch, except when there is no high-grading ($\hat{P} = P_{min}$).

The weight of the total stock of fish is fixed at $\tilde{Q}$. Total catch during the season cannot exceed this biological limit. It is assumed that $\overline{Q} \leq \tilde{Q}$.

Profit maximisation problem

The operator's problem involves choosing the total catch (Q) and the critical price , $\hat{P}$, below which fish are to be discarded, in order to maximise profit. The operator assumes that his or her actions have a negligible effect on the market prices of inputs and outputs and the distribution of fish grades in any period. Formally, the maximisation problem is as follows:

$$\underset{Q,\hat{P}}{MAX}\,\Pi = Q.\int_{\hat{P}}^{P_{max}} Pf(P)dP - C(Q)$$

subject to the constraints that:

(1a) $$\overline{Q} \geq Q$$

(1b) $$Q \geq 0$$

(1c) $$\overline{Q} \geq QF(\hat{P})$$

(1d) $$P_{max} \geq \hat{P}$$

(1e) $$\hat{P} \geq P_{min}$$

- a twice differentiable cost function, $C(Q)$, that gives the minimum operating cost associated with catching Q tonnes of fish during the season for a given, and unchanging, set of input prices;

- a distribution function, $F(\hat{P}) = \int_{\hat{P}}^{P_{max}} f(P)\ dP$, that gives the proportion of fish with prices above or equal to $\hat{P}$ in a catch of any given weight; and

- a price P_{min}, equal to the lowest price of fish in the catch (so $F(P_{min})=1$).

It is assumed: that operating costs are increasing at non-decreasing rate as catch rises (so $C'(Q) > 0$ and $C''(Q) \geq 0$; and that the density function $f(P)$ is continuous on the closed interval $[P_{min}, P_{max}]$.

Given this technology the operator is able to target fish with prices in the range P_{min} to P_{max}. However, the distribution of grades within the catch cannot be altered, for example, by changing inputs or targeting practices. This means that, in the model presented here, discarding low priced fish at sea, or high-grading, is the only means available to increase the average unit price of a catch. It is also implied that all fish caught are worth bringing to market including any damaged fish.

High-grading

When high-grading, the operator discards all fish with prices below some critical level denoted by $\hat{P}$. Given this, the reported catch is equal to $Q.F(\hat{P})$.

The cost of grading fish according to price is incorporated in the cost function $C(Q)$. The implication here is that fish must always be graded, even when there is no high-grading. The direct cost associated with throwing low priced fish overboard is assumed to be negligible. However, by high-grading, the operator is likely to increase the average cost of harvesting the catch that is actually landed on shore.

Implicitly, it is assumed that the operator is able to discern the grade of each fish while at sea and to discard low priced fish while out of the view of fishing authorities. If there was a probability of being caught and subsequently fined, then this could impact significantly on the expected costs of high-grading. Hence the level of high-grading that actually occurs may also be affected. Such costs are ignored. Also, high-grading is assumed to be the only

Expression (1a) is the biological constraint, (1b) is a non-negativity constraint and (1c) is the quota constraint that places a limit on the operator's reported catch. Expressions (1d) and (1e) are technological constraints representing the assumption that operators must target fish with prices in the closed interval $[P_{min}, P_{max}]$.

A solution to the maximisation problem exists because Π is continuous and the set from which maximisers can be chosen is compact. Let P^* and Q^* denote profit maximising values of $\hat{P}$ and Q respectively. These must satisfy the following first order conditions:

(2a) $$\int_{P^*}^{P_{max}} (P-\lambda_2) f(P) dP - C'(Q^*) - \lambda_0 + \lambda_1 = 0$$

(2b) $$Q^* f(P^*)[\lambda_2 - P^*] - \lambda_3 + \lambda_4 = 0$$

(2c) $$[\bar{Q} - Q^*]\lambda_0 = 0$$

(2d) $$Q^* \lambda_1 = 0$$

(2e) $$[\overline{Q} - Q^* F(P^*)]\lambda_2 = 0$$

(2f) $$[P_{max} - P^*]\lambda_3 = 0$$

(2g) $$[P^* - P_{min}]\lambda_4 = 0$$

where $\lambda_0, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ are non-negative Lagrange multipliers.

To increase the ease with which results can be interpreted some assumptions about the solution to the operators maximisation problem are made. First it is assumed that actual catch Q^* is strictly positive. This implies that it never pays to discard the entire catch when high-grading. Second, it is assumed that it is not sufficiently profitable to catch the entire stock in a single season and therefore the biological constraint (1a) is non-binding. The implications of these assumptions are outlined in the appendix.

3. The optimal level of high-grading

Based on the model developed in the previous section it is possible to determine conditions under which high-grading might take place and the proportion of fish that are likely to be discarded.

First, from equations (2b), (2e) and (2g) it follows that $P^* > P_{min}$ only if $\overline{Q} = Q^* F(P^*)$. Therefore, in years when the catch quota is non-binding, for example because of poor seasonal conditions, the operator will not discard any marketable fish. This highlights the link between the imposition of a quota restriction and the emergence of high-grading.

When high-grading does take place, the critical price level below which fish are discarded is given by the unique solution to the following equality (see the appendix for a proof):

(3) $$\int_{P^*}^{P_{max}} Pf(P)dP - P^* F(P^*) - C'\left(\frac{\overline{Q}}{F(P^*)}\right) = 0$$

According to expression (3) the operator sets P^* to equate the average price of the reported catch,

$$\int_{P^*}^{P_{max}} Pf(P)dP,$$

to the marginal cost of fishing. This is made up of:

- the operating cost of catching the marginal unit of fish, $C'\left(\frac{\overline{Q}}{F(P^*)}\right)$; as well as
- $P^*F(P^*)$ which is equal to the cost, in terms of revenue, associated with discarding additional fish of a marginally lower price than P^*.

Based on (3), the following condition is both necessary and sufficient for an incentive to high-grade to exist (see the appendix for a proof):

(4) $$\int_{P_{min}}^{P_{max}} Pf(P)dP - P_{min} > C'(\overline{Q})$$

where P_{min} is the price of the lowest quality fish grade in the population and $\int_{P_{min}}^{P_{max}} Pf(P)dP$ is the average price of fish in an ungraded catch.

Inequality (4) implies that, from the point of view of the private operator, high-grading is efficient behaviour, if for example:

- marginal fishing costs are sufficiently low;
- the price of the lowest priced fish is sufficiently low; or,
- the proportion of high grade fish in an ungraded catch is sufficiently high, thereby reducing the opportunity cost associated with discarding low priced fish.

Inequality (4) might be used in empirical work to indicate whether high-grading might take place in a fishery if catch quotas were imposed. It is important to note, however, that if operators can alter their fishing technology following the introduction of the catch quota, in order to target higher grades of fish, then using the pre-quota density function, f(P), in condition (4) could give misleading results.

4. The impact of price changes on the catch size

High-grading allows operators to alter their catch in response to a change in the price of fish. This observation is important from the perspective of fisheries management because it means that, even with catch quotas in place, the sustainability of stocks depends on changing market factors. As a result, price changes from year to year may need to be taken into account when determining the total catch quota that meets the economic and biological objectives of the fishery's management program.

It is important to be able to consider price shocks that affect different grades of fish at differing rates. To model these types of changes assume that the price shock results in an increase in the price of fish, from P to

(5) $$P + [\omega - 1]g(P)$$

The function $[\omega - 1]g(P)$ is assumed to be differentiable in P and w is a real valued parameter, set equal to 1 prior to the price change. It is important to assume that the price shock leaves the ranking of grades unaltered so that if $P_a > P_b$ then $P_a + [\omega - 1]g(P_a) > P_b + [\omega - 1]g(P_b)$. This is equivalent to assuming that

(6) $$[\omega - 1]g'(P) > -1.$$

Modelling price changes according to (5) offers a great deal of flexibility. For example, if the function $[\omega - 1]g(P)$ is increasing in P, the absolute increase in the prices of high grade fish would be lower than the absolute increase in the prices of lower grade fish. On the other hand if the prices of middle grade fish rise more than other grades, $g(P)$ would peak in the open interval $[P_{min}, P_{max}]$. However, the magnitude of this peak would be constrained according to (6).

The following formula gives the percentage change in output following shifts in the prices of all qualities of fish resulting from a marginal increase of $d\omega$ in the parameter ω (see appendix).

(7)
$$\varepsilon_1 = \frac{d\omega\left[\int_{P^*}^{P_{max}} g(P)f(P)dP - g(P^*)F(P^*)\right]}{\frac{F(P^*)^2}{f(P^*)} + C''\left(\frac{\bar{Q}}{F(P^*)}\right)\frac{\bar{Q}}{F(P^*)}}$$

where $d\omega \int_{P^*}^{P_{max}} g(P)f(P)dP$ is the change in the average price of the reported catch following the price shock.

Given non-decreasing marginal costs, the denominator of the price elasticity in (7) is positive. Therefore, the direction of output change following a price shift depends on the sign of the numerator (given (6) the numerator may be either positive or negative). In particular, output rises (falls) if a marginal increase in all prices leaves the average change in the price of the reported catch greater (less) than the change in the price of the lowest quality fish retained in the catch (weighted by $F(P^*)$). Also, note that the elasticity is well defined even when marginal costs are constant.

To explain the result in (7) note that $d\omega\left[\int_{P^*}^{P_{max}} g(P)f(P)dP - g(P^*)F(P^*)\right]$ is the marginal change in revenue following the price change. Consider a reduction in this revenue resulting from a greater increase in the price of lower quality fish relative to high quality fish, so that $d\omega\left[\int_{P^*}^{P_{max}} g(P)f(P)dP - g(P^*)F(P^*)\right]$ is negative. Following this reduction, marginal operating cost exceeds marginal revenue and a loss is being made on the last units of catch. Therefore catch must decline.

The formula in (7) can be used to give the percentage change in catch resulting from a uniform percentage increase in the price of all grades of fish. This is given by expression (8).

(8)
$$\varepsilon_2 = \frac{C'\left(\frac{\overline{Q}}{F(P^*)}\right)}{\frac{F(P^*)^2}{f(P^*)} + C''\left(\frac{\overline{Q}}{F(P^*)}\right)\frac{\overline{Q}}{F(P^*)}}$$

The elasticity in (8) is strictly positive meaning that a uniform percentage increase in the price of all qualities of fish leads to an increase in total catch and by implication an increase in the proportion of fish that are discarded.

This result can be explained by noting that an equal percentage increase in the prices of all fish leads to greater absolute increases in the prices of higher grade fish relative lower grade fish. As a result the opportunity cost associated with retaining lower grades of fish increases. Therefore, the level of discarding increases and true catch levels rise so that reported catch can meet the catch quota.

5. The impact of changes to the catch quota on catch size

One method employed in some fisheries to reduce the amount of excess catch resulting from high-grading is to reduce the size of the catch quota. To illustrate the impact of such a policy on total catch, the following formula gives the percentage reduction in catch resulting from a marginal reduction in the catch quota (see appendix). It is assumed that the change in quota has no effect on market prices generally.

(9)
$$\frac{dQ^*}{d\overline{Q}}\left[\frac{\overline{Q}}{Q^*}\right] = 1 - \nu$$

where

(10)
$$\nu = \frac{C''\left(\frac{\overline{Q}}{F(P^*)}\right)}{\frac{F(P^*)}{\overline{Q}f(P^*)} + C''\left(\frac{\overline{Q}}{F(P^*)}\right)}$$

and $0 \leq \nu < 1$

The result shows that when marginal operating costs are an increasing function of catch, a reduction in the quota leads to a less than proportionate reduction in the amount caught.

On the other hand when marginal operating costs are constant ($C'' = 0$), a reduction in the quota leads to an equi-proportionate reduction in the amount caught.

To see the reasoning behind this result, consider a 1 per cent reduction in the catch quota. In order to meet this new quota, the operator could reduce catch by 1 per cent, increase the proportion of fish that are discarded, or combine both strategies. When marginal costs are increasing, a 1 per cent reduction in catch, would lead to a decline in marginal cost relative to marginal revenue and as a result profit could be increased with a greater catch. Therefore, the least cost way to meet the new constraint, would be to lower catch by less than 1 per cent and to discard a relatively higher proportion of this reduced catch. On the other hand, when ($C'' = 0$), changes to output have no effect on marginal operating cost. Therefore, the least cost way to satisfy the reduced catch quota constraint is to reduce total catch by 1 per cent without changing the proportion of fish that are discarded.

From a fisheries management perspective, if marginal costs are known to be constant and it is observed (or estimated) that x per cent of fish are discarded, then the total catch quota could be set at $(100 - x)$ per cent of the estimated seasonal catch level estimated to meet the economic and biological objectives of the fishery. If, on the other hand marginal costs are known to increase, then the quota would need to be set at less than $(100 - x)$ of the estimated optimal catch level and according to an estimate of in expression 10.

6. Measuring profit in the presence of high-grading

Estimating profit levels in fisheries affected by high-grading is problematic. For example, when modelling the potential profits associated with the introduction of catch quotas, if the average future prices and costs are estimated using observed pre-quota prices and costs, profit could be underestimated.

Based on the model described in section 2, when marginal cost is constant and in the presence of high-grading, profit (excluding fixed costs) is given by expression 11 (see appendix).

(11) $$\Pi = P^* \overline{Q}$$

where P^* is the price of the lowest priced fish in the reported catch. The expression is easy to calculate as it does not depend on the distribution of prices over grades, the distribution of the fish population over grades, or the level of fishing costs.

An explanation for the formula in expression 11 should begin with the observation that in the presence of high-grading, P^* is the shadow price of the catch quota (from expression (2a) $\lambda_2 = P^*$ when $\lambda_4 = 0$). Intuitively, if the quota is relaxed marginally, the operator increases output by an equi-proportionate amount (see previous section) earning an additional profit of $\dfrac{\int_{P^*}^{P_{max}} Pf(P)dP - C'\left(\dfrac{\overline{Q}}{F(P^*)}\right)}{F(P^*)}$ on the marginal unit of quota. At the margin; however, this level of profit must equal the marginal benefit associated with discarding fewer units of fish from expression 3. This benefit is equal to P^* from expression 3.

If marginal cost is increasing, the right hand side of expression 11 places an upper limit on fisheries rent. In this case a more accurate expression for profitability in the presence of high-grading is given by:

$$\Pi = P^*\overline{Q} - [C'(Q^*) - AVC(Q^*)]Q^* \tag{12}$$

where $AVC(Q^*)$ is the average variable unit cost of catching $Q^* = \dfrac{\overline{Q}}{f(P^*)}$. The more that marginal costs increase relative to average costs, the greater is the difference between actual economic profit and $P^*\overline{Q}$.

7. Example using data from the Australian northern prawn fishery

At present, catch levels in the northern prawn fishery are managed using a set of input controls that limit gear units and boat numbers[3]. A number of alternative long term management options have been considered by industry and government (NORMAC Working Group on Fisheries Management Arrangements, 1992) including the introduction of individual transferable catch quotas, current ABARE research, study of alternative management systems for the northern prawn fishery, has shown that it may be profitable for fishermen to discard some grades of prawns, if individual transferable catch quotas are introduced.

3 The northern prawn fishery is located in Commonwealth waters in the Australian Fishing Zone between Cape Londonderry and Cape York. It covers about 1 million square kilometres of water, making it one of Australia's largest fisheries by area.

Data from the northern prawn fishery are used to illustrate some of the results obtained here. The focus is on tiger prawns, which on average represent about 40 per cent of the total catch. However, tiger prawns contribute about 75 per cent to revenue and account for about 70 per cent of total fishing effort. Banana prawns, which account for just under 50 per cent of the total catch, are caught at the start of the fishing season (usually April and May) and most operators target Tiger Prawns for the remainder of the season to December.

Assumptions

Average prices of Tiger prawns by grade for the years 1990 to 1992 and the average proportions of the different grades in total catch are shown in table 1.

It is assumed from current ABARE research that interest, depreciation, repair and insurance costs associated with capital are fixed in any given season and the marginal cost of fishing is set at a constant $4.80/kg of tiger prawns.

A 4000 tonne total catch quota is assumed to apply for tiger prawns. This level is consistent with the maximum sustainable annual yield for tiger prawns in the northern prawn fishery as estimated by Somers (1992). Such a quota is likely to have been binding in 1991 but not in 1990 and 1992 when harvest levels were well below normal because of adverse seasonal conditions.

The optimal level of high-grading

Using expression (4), and assuming that the distribution of prawn grades within the catch would have remained the same if catch quotas had been in place, the model indicates that

Table 1: Average price of tiger prawns

Grade weight (prawns per pound)	Weight per prawn (grams)	Nominal price 1990 ($/kg)	1991 ($/kg)	1992 ($/kg)	Proportion caught a (% of weight)
< 10	> 45	19.68	16.61	18.88	53
10 to 15	30 – 45	14.56	10.96	13.40	27
16 to 20	23 – 29	13.97	9.06	12.30	7
21 to 30	15 – 22	10.50	6.77	9.60	3

a Based on average data from 1989-1990

in 1991 fishermen would have found it profitable to discard all fish valued below the average price of the 16-20 per kilo range; so, $P^* = \$9.06$/kg. High-grading would not have been expected in 1990 and 1992 when the assumed quota constraint would not be expected to have been binding.

This result is consistent with studies at ABARE which found that fishermen would have profited from discarding all prawns above the 15 per pound grade in 1991. However, it was noted that some operators may run into time constraints when trying to replace the discarded prawns.

This analysis may be difficult to apply prior to the start of any particular season due to uncertainty surrounding future prices and the size distribution of the stock for that year (which may also impact on the setting of the total allowable catch in the first place). However, the analysis may be able to be applied once the season has begun based on estimates of distribution of catch and price from early season landings. The model may also be useful in a post season analysis of the extent of high-grading, particularly if this has an impact upon the level of the total allowable catch in the following year.

The responsiveness of output to price changes

As marginal costs are assumed to be constant at \$4.80/kg, the percentage change in output following an 1 per cent increase in the prices of all grades of prawn is given by equation expression 13.

(13)
$$\varepsilon_2 = \frac{4.8 f(P^*)}{F(P^*)^2}$$

The formula is applicable only for 1991 when high-grading could have been expected. Based on the data in table 1, $f(9.06)$ is approximately equal to 0.035 and $F(9.06)$ is 0.90; that is, 10 per cent of prawns would have been discarded. Therefore, if prices had been 1 per cent price higher in 1991, catch would have been about 0.21 per cent higher.

Profitability

Expression 11 can be used to estimate the annual profit, excluding fixed costs associated with capital, that would have been generated from the tiger prawn component of the northern prawn fishery with the introduction of catch quotas in 1991 (the formula is not applicable to 1990 and 1992).

Maximum profit, excluding fixed costs, is estimated at $36.4 million, ($9.06 x 4000 tonnes). This figure is consistent with the gross margin (accounting for a normal return to operators) of $37 million obtained by ABARE research for the 1991 base year, accounting for a normal rate of return to operators.

Caveats

The estimates obtained above should be regarded with some caution as there are factors in the northern prawn fishery that may not be consistent with the underlying assumptions outlined in section 2. In particular, there is some evidence from ABARE research that operators in the northern prawn fishery target larger prawns if they wish to. This means that fishermen could increase the average value of their catch with less high-grading than implied by the model presented here.

7. Extensions and conclusions

The model developed in section 3 is based on a number of restrictive assumptions. However, the model can be extended in a number of directions without losing the basic results obtained here.

- It has been assumed that there is a single species (or alternatively that the catch quota applies to the whole catch and not to individual species). This restriction can be relaxed to consider fisheries with a number of species and where quotas for different species may be transferred between operators.
- The model encapsulates decisions taken over a whole season as if they were taking place in a single period. The model can be extended to take account of the way in which the factors affecting high-grading might change over time within a season.
- High-grading in fisheries managed using input controls could be investigated. For example, a constraint that limits the quantity of fish that can be stored on board would have similar implications for high-grading to those from the catch quota. On the other hand, restrictions that just increase marginal costs would not be expected to cause high-grading.

One important feature, not considered here, is the problem of uncertainty relating to fish prices and population distributions. For example, if there is uncertainty about the grades of fish that might be obtained following the discarding of low priced fish, risk averse operators may discard fewer fish than would be predicted using the model presented here.

It will also be important to consider the impact of allowing operators to change fishing techniques in order to target higher price fish. Such analysis would be of particular importance in fisheries where operators can significantly improve targeting (at a relatively low cost) following the introduction of catch quotas.

Implications for fisheries management and modelling

The results obtained here indicate that high-grading may be a significant problem in fisheries that are managed using catch quotas. In this paper formulas are provided to indicate when high-grading may be a problem (expression 3) and the proportions of fish that might be discarded (expression 4). Such indications provide information that may be useful when setting catch quotas and measuring population trends. The usefulness of this model in stock assessment may depend on the cost and ability of obtaining discard estimates through alternative means, such as fishery surveys, and on the stock assessment technique being employed. It is unlikely that detailed length and age data, needed for some stock assessments, would be forthcoming from this model.

With high-grading it is evident that catch levels may be sensitive to price. It is therefore important to account for economic as well as biological factors when estimating population trends, even in fisheries that are managed using catch quotas. In particular it is shown that output may decline if the average price of the reported component of the catch rises less than the price of the lowest quality fish in the catch. Formulas that give the change in total output resulting from given changes in the prices of different qualities of fish are provided in expressions (7) and (8).

In fisheries where high-grading is a problem, catch can be reduced by lowering the catch quota. It is shown that when marginal cost is constant, reductions in the quota lead to proportionate reductions in catch. However, if, marginal costs are increasing, the reduction in quota could lead to an increase in the proportion of discarded fish. This means that a reduction in the quota would lead to a smaller reduction in catch, indicating that the rate at which costs change as catch increases could be an important determinant in setting catch quotas.

Finally, it is shown that models which do not account for high-grading could tend to underestimate potential short term profitability following the introduction of catch quotas. To help overcome these problems, expressions (11) and (12) give formulae that allow the annual profit (excluding fixed costs) in fisheries affected by high-grading to be calculated in a relatively simple manner.

Appendix

First note, that by assumption $Q^* > 0$ and $Q^* < \tilde{Q}$. As a result, $\lambda_1 = 0$ and $\lambda_0 = 0$. Also, since $Q^* > 0$ profit will be negative if $P^* = P_{max}$ so $\lambda_3 = 0$.

It can be shown, when $\tilde{Q}$ is sufficiently large, that (1*a*) $Q^* < \tilde{Q}$

Proof:

Since $\overline{Q} \le \tilde{Q}$, if $Q = \tilde{Q}$ it follows that $\frac{\overline{Q}}{\tilde{Q}} = F(P^*)$. In this case, revenue from fishing is given by $\frac{\overline{Q}}{F(\hat{P})}\int_{\hat{P}}^{P_{max}} Pf(P)dP$. This expression increases as $\hat{P}$ rises and L'Hopital's rule can be used to show that it is bounded above by $P_{max}\overline{Q}$. On the other hand, since $C''(Q) \geq 0$, operating cost is unbounded above as $\tilde{Q}$ rises. Therefore, for sufficiently large values of $\tilde{Q}$, Π is negative. Since $\Pi=0$ is feasible, it follows that $Q^* < \tilde{Q}$.

Expression 3

In the presence of high-grading P^* is given by the unique solution to (3).

Proof:

Assume there is high-grading. From (2g) it follows that $\lambda_4 = 0$. From (2b) it follows that $\lambda_2 = P^*$ and therefore, $\overline{Q} = Q^* F(\hat{N}^*)$. At an optimum, therefore, $\int_{P^*}^{P_{max}} Nf(N)dN - P^* F(P^*) - C'(\frac{\overline{Q}}{F(P^*)}) = 0$. As Π and $QF(\hat{P})$ (from constraint 1c) are not concave in $\hat{P}$, the Kuhn Tucker theorem cannot be applied to show that the solution to 3 is indeed the maximiser. Instead, consider the following derivation.

The derivative of $\int_{P^*}^{P_{max}} Pf(P)dP - P^* F(P^*) - C'(\frac{\overline{Q}}{F(P^*)})$ with respect to P^* is $-F(P^*) - C''(\frac{\overline{Q}}{F(P^*)})\frac{\overline{Q}.f(P^*)}{F(P^*)^2}$ which is strictly negative and continuous. $\int_{P^*}^{P_{max}} Pf(P)dP - P^* F(P^*) - C'(\frac{\overline{Q}}{F(P^*)})$ is negative as P^* approaches P_{max}. Also, it is shown in the proof for expression 4 that when $P=P_{min}$ and when there is high-grading, it follows that $\int_{P_{min}}^{P_{max}} Nf(N)dN - p_{min} > C'(\overline{Q})$. Therefore, a unique solution for P^* can be found. Since this solution is unique, it must be a maximiser.

Expression 4

$\int_{P_{min}}^{P_{max}} Nf(N)dN - p_{min} > C'(\overline{Q})$ is necessary and sufficient for an incentive to high-grade to exist

Proof:

Sufficiency

Assume there is no high-grading; that is $\hat{P} = P_{min}$. It follows from (2f) that $\lambda_4 \geq 0$. Substituting for λ_2 from (2b) into (2a) it follows that $\int_{P_{min}}^{P_{max}} Nf(N)dN - P_{min} - C'(Q^*) \leq 0$. Noting

$\overline{Q} \geq Q^*$ and $C''(Q) \geq 0$ it follows that $\int_{P_{min}}^{P_{max}} Nf(N)dN - P_{min} \leq C'(\overline{Q})$. Therefore, if, (3) holds, $P^* \neq P_{min}$. Since a maximum exists it follows that $P^* > P_{min}$ and there is high-grading

Necessity

At an optimum, $\int_{P^*}^{P_{max}} Nf(N)dN - P^* F(P^*) - C'(\frac{\overline{Q}}{F(P^*)}) = 0$. As $C''(Q) \geq 0$ the left hand side of this expression is decreasing (strictly) in P^* (see above). The necessity of condition (3) follows.

Expression 7

$$\varepsilon_1 = \frac{d\omega\left[\int_{P^*}^{P_{max}} g(N)f(N)dN - g(P^*)F(P^*)\right]}{\frac{F(P^*)^2}{f(P^*)} + C''\left(\frac{\overline{Q}}{F(P^*)}\right)\frac{\overline{Q}}{F(P^*)}}$$

Proof:

First note that a more general expression for (3) is given by $\int_{P^*}^{P_{max}} [N + [1-\omega]g(N)]f(N)dN - [P^* + [1-\omega]g(P^*)]F(P^*) - C'(\frac{\overline{Q}}{F(P^*)}) = 0$. Differentiating this expression totally with respect to P^* and ω gives,

$$dP^* = \frac{d\omega\left[\int_{P^*}^{P_{max}} g(N)f(N)dN - g(P^*)F(P^*)\right]}{F(P^*) + C''\left(\frac{\overline{Q}}{F(P^*)}\right)\frac{Q^* f(P^*)}{F(P^*)}}$$

Noting that $\varepsilon_1 = \frac{dQ^*}{Q^*} = \frac{\overline{Q}}{Q^*}\frac{f(P^*)}{F(P^*)^2}dP^*$ yields the result.

Expression 8

$$\varepsilon_2 = \frac{C'\left(\frac{\overline{Q}}{F(P^*)}\right)}{\frac{F(P^*)^2}{f(P^*)} + C''\left(\frac{\overline{Q}}{F(P^*)}\right)\frac{\overline{Q}}{F(P^*)}}$$

Proof:

Noting that $\varepsilon_2 = \dfrac{dQ^*}{Q^*} \Big/ d\omega$, $[\omega\text{-}1]g(P)=[\omega\text{-}1]P$ and (3) yields the result.

Expressions 9 and 10

$$\frac{dQ^*}{d\overline{Q}}\left[\frac{\overline{Q}}{Q^*}\right]=1-\nu$$

where

$$\nu=\frac{C''(\frac{\overline{Q}}{F(P^*)})}{\frac{F(P^*)^2}{\overline{Q}f(P^*)}+C''(\frac{\overline{Q}}{F(P^*)}).F(P^*)}$$

Proof:

Obtained by totally differentiating (3) with respect to P^* and ω to obtain

$$\frac{dP^*}{d\overline{Q}}=\frac{C''(\frac{\overline{Q}}{F(P^*)})}{-F(P^*)-C''(\frac{\overline{Q}}{F(p^*)})\frac{\overline{Q}f(P^*)}{F(P^*)^2}}$$ and noting that $$\frac{dQ^*}{d\overline{Q}}=\frac{1}{F(P^*)}+\frac{\overline{Q}f(P^*)}{F(P^*)^2}\frac{dP^*}{d\overline{Q}}$$

yields the result.

Expression 11

When marginal cost is constant and in the presence of high-grading, rent (economic profit excluding fixed costs) is given by the following expression

$$\Pi=P^*\overline{Q}$$

Proof:

Obtained by multiplying (3) through by Q* and by noting that $\overline{Q} = Q^*.F(P^*)$.

Expression 12

$$\Pi = P^* \overline{Q} - [C'(Q^*) - AVC(Q^*)]Q^*$$

Proof:

Obtained by multiplying (3) through by Q^*, by noting that $\overline{Q} = Q^*.F(P^*)$ and that $C(Q^*) = AVC(Q^*)Q^*$.

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