

**HOW TO SET CATCH QUOTAS: A NOTE ON THE
SUPERIORITY OF CONSTANT EFFORT RULES**

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HOW TO SET CATCH QUOTAS: A NOTE ON THE SUPERIORITY OF CONSTANT EFFORT RULES

Interest in the economic performance of various rules for the controlled exploitation of fisheries is increasing. In a recent paper, Hannesson and Steinshamn [1] compare the performance of constant effort and constant catch rules in the presence of fluctuating stocks. More precisely the comparison is between a given constant effort rule and a constant catch rule yielding the same average catch. Their approach is to compare average revenue and average costs under the two rules. Under most plausible conditions constant effort rules yield higher average revenues, but involve higher average cost. Hannesson and Steinshamn therefore conclude that neither rule is generally superior, and conjecture that the optimal rule will be some mixture of the two.

The purpose of this note is to show that, provided the marginal revenue return to effort is an increasing function of stocks, the constant effort rule will be superior in the following strong sense. For every constant catch rule, there exists a constant effort rule yielding higher net profit with probability 1. The basic argument is as follows. The optimal fishing rule is derived for the case when the stock is known *ex ante*. It is shown that this rule calls for higher effort in years when stocks are high and the marginal cost of catch is correspondingly low. A constant catch rule yields lower effort in these years, and higher effort in years when stocks are low. Hence the effort under the constant catch rule is always further away from the optimum than a constant effort set equal to the effort required for the stock level at which the given constant is optimal.

The notation of Hannesson and Steinshamn will be followed. Fishing catch is given by

$$x = F(z,y)$$

where x is catch, z is effort and y is the stock of fish (assumed independently and identically distributed over time). The stock y is purely stochastic and cannot be influenced by the human action. Given the monotonicity assumptions $F_z, F_y > 0$, F defines an effort requirement function $G(x,y)$. Profit is given by

$$\pi(x, y, z) = R(x) - C(z) \quad (1)$$

where $R(x) = P(x)x$ is revenue and $C(z)$ is the cost of calling forth the effort $z = G(x,y)$. Insight into the stochastic case may be obtained by considering the case where the stock level is known at the time fishing effort decisions are made. Assuming that y is known, it is straightforward to derive the first-order condition on z

$$R_x F_z - C_z = 0 \quad (2)$$

and the second order condition

$$D = R_x F_{zz} + R_{xx} F_z^2 - C_{zz} < 0$$

At z^* , the optimal level of z , it is necessary that $R_x > 0$, that is, that the industry should face an elastic demand curve. The term $R_x F_z = dR/dz$ is the marginal revenue return to effort.

Implicit differentiation with respect to y now yields

$$z^*/y = (-1/D) (R_x F_{zy} + R_{xx} F_z F_y) = (-1/D) (/ y (dR/dz)) \quad (3)$$

Hence $z^*/y > 0$ if and only if $/ y (dR/dz) > 0$. It is now possible to prove the main result

Proposition 1: Assume $/ y (dR/dz) > 0$. Then for any constant catch, there exists a constant effort level yielding a higher profit with probability 1.

Proof: Let the constant output level be denoted \bar{x} . Suppose there exists a stock

level y_0 such that $\bar{x} = F(y_0, z^*(y_0))$. Then, for any y , $y > y_0 \implies z^*(y) > z^*(y_0) > G(\bar{x}, y)$ and $y < y_0 \implies z^*(y) < z^*(y_0) < G(\bar{x}, y)$. By concavity of the profit function, this implies

$$(\bar{x}, y, G(\bar{x}, y)) \leq (F(z^*(y_0), y, z^*(y_0))) \leq y, \text{ with equality only for } y=y_0$$

Note that the converse does not apply. If z^*/y is negative but small, the optimal effort for any given y will lie between $G(\bar{x}, y)$ and $z^*(y_0)$, but will be close to $z^*(y_0)$, so that the constant effort rule will still be superior.

It is useful to consider the requirement that $\partial y (dR/dz) > 0$ in more detail. A sufficient condition is that $R_{xx} < 0$. This condition will be satisfied (with equality) in two interesting cases. The first is that of perfectly elastic demand resulting in a price P which is independent of the catch level. The second is where price is of the form

$$P(x) = P_0 + a/x.$$

The second type of price function represents a case where price asymptotically approaches a world market price. The case of perfectly elastic demand is of interest in its own right. It is also important if the management objective is not profit maximization but social welfare maximization. In this case, management is not concerned with monopoly rents and condition (1) must be replaced with the requirement that $C_z = pF_z$.

An analysis in terms of catchability, following McCall [2] provides an alternative set of sufficient conditions. Suppose that as stock decreases, the area over which it is distributed decreases proportionally, but schooling behavior is unaffected, so that the concentration of fish within the area in which fish are present remains constant. The cost of locating a given school and harvesting it at a given intensity is essentially independent of the stock (that is, of the number of schools). If demand is perfectly elastic, it is clear that the optimal policy is to harvest every school at the same level of intensity. In this case, the optimal policy is one which makes effort directly proportional to stocks. When demand is not perfectly elastic (note that equilibrium requires that the

elasticity of demand be greater than 1), optimal effort will increase with the stock level, but not proportionally.

A constant catch rule may have particularly undesirable results in this case. Suppose that the optimal policy involves a catch rate c , and that a constant catch \bar{x} is imposed. When stocks are large so that $cy > \bar{x}$, profitable opportunities will be unexploited. Fishing effort will be confined to a limited area, when stocks outside that area could be profitably harvested. When stocks are low and $cy < \bar{x}$, the constant catch rule involves catching an increased proportion of the residual stock, at a cost which increases with the intensity of exploitation. In extreme cases, the constant catch rule may be simply infeasible. The constant effort rule is also sub-optimal, but is strictly superior to the constant catch rule, since the deviation from the optimum is smaller.

The results presented above provide a strong presumption in favor of constant effort rules. There are, however, demand structures for which the relevant conditions will not be satisfied. One is presented in Hannesson and Steinshamn's Table VII, where it is assumed that the price is constant up to \bar{x} and zero thereafter. In this case, any effort beyond that required to produce \bar{x} is clearly wasted.

The theoretical model presented here, like that of Hannesson and Steinshamn, is based on the assumption that stocks are independently and identically distributed over time. The results do not, therefore, apply directly to the complex quasi-empirical model they apply to Arcto-Norwegian cod. However, it may be of interest to consider some simple dynamic extensions of the results derived above. Consider a simple dynamic model such as that of Scott [2] in which future stocks depend on current stocks, by a way of a simple concave increasing function (that is, the proportional growth rate of stocks is a diminishing function of current stocks). Then the first-order condition (1) must be modified to include a term for the marginal effect of increased current catch on future stocks. With the assumptions described here, it is easy to see that this term will be smaller, the larger is the current stock. Hence, *ceteris paribus*, the optimal effort will

be larger when stocks are large. This will reinforce the result in Proposition 1.

Another useful extension is to the case of a multi-species fishery. Hannesson and Steinshamn developed their model in the context of the Arcto-Norwegian cod fishery, where there is only one commercially important target species. The simplest case of a multispecies fishery is that where the scalar values of stocks and catch levels are replaced by vectors, so that

$$\mathbf{x} = F(\mathbf{y}, z)$$

This formulation implies that the catch of each species depends on the total stock, but that fishing effort cannot be targeted at any particular species. The analysis presented above goes through with appropriate modifications. The revenue function becomes $R(\mathbf{x}) = \mathbf{x} \cdot \mathbf{p}(\mathbf{x})$, where $\mathbf{p}(\mathbf{x})$ will, in general, be determined by a system of demand equations for fish. It is not possible, for arbitrary \mathbf{x} , \mathbf{y} to define an effort level which will yield output \mathbf{x} when the stock vector is \mathbf{y} . However, it is possible to define an effort requirement function $G(R, \mathbf{y})$, the effort required to obtain revenue level R when the stock vector is \mathbf{y} . The first and second order conditions on z may be replaced by the corresponding conditions

$$\mathbf{R}_x \cdot \mathbf{F}_z - C_z = 0$$

and

$$D = \mathbf{R}_x \cdot \mathbf{F}_{zz} + \mathbf{F}_z' \mathbf{R}_{xx} \mathbf{F}_z - C_{zz} < 0$$

where \mathbf{R}_x , \mathbf{F}_z and \mathbf{F}_{zz} are vectors of partial derivatives, and \mathbf{R}_{xx} is a matrix.

A change in \mathbf{y} will be defined to be an increase in stock availability if it results in a reduction in $G(R, \mathbf{y})$ in a neighborhood of the initial pair (R, z) , and a reduction in stock availability if it leads to an increase in $G(R, \mathbf{y})$.

The main problem is that there is no obvious way of defining a constant catch rule in this case. The production technology makes it infeasible to impose separate catch rules for each of the target species. It is necessary to constrain total output as defined by

some weighted average. In particular, if the target species are weighted by the marginal revenue they yield, it is possible to impose a constant gross revenue rule.

We are now ready to prove

Proposition 2: Assume that an increase in stock availability leads to an increase in dR/dz . Then for any constant revenue R , there exists a constant effort level yielding a higher profit with probability 1.

Proof: The proof follows that of Proposition 1, with \bar{x} replaced by R , and the condition $y > y_0$ replaced by the requirement that y is an increase in stock availability relative to y_0 . \square

A more general form of multi-species fishery is that where effort can be targeted at particular species to some extent, so that the production technology is of the form $F(\mathbf{x}, \mathbf{y}, z) = 0$. The analysis leading to Proposition 2 is essentially unchanged, given the behavioral assumption that \mathbf{x} is always chosen to maximize R for given \mathbf{y} and z .

The extension to the multi-species case raises the question of whether the scalar effort measure z may be replaced by a vector of inputs \mathbf{z} . The use of a single effort measure z is justified where the production technology is separable in \mathbf{y} and \mathbf{z} . In this case, a scalar measure of inputs \mathbf{z} may always be obtained. There may, however be practical difficulties in observing all the inputs. If a subset of the input vector, such as boat size and number of fishing days, is used as a proxy for effort, there will be an incentive, in fisheries with multiple users, to make more use of uncontrolled inputs. When the production technology is not separable, there will be difficulty in defining an appropriate scalar measure of effort even if all inputs are observable. These issues are beyond the scope of the present note.

Finally, it may be worth considering the possibility of an optimal strategy. If management authorities know the technology F , and can monitor both effort and catches, as has implicitly been assumed here, they can infer the stock level $y = H(x, z)$, and can therefore set the optimal effort and catch levels satisfying (1). How might this work in

practice? Suppose the fishery has a single owner (to avoid incentive problems) and that effort is determined by the number of fishing days. Then it is possible to prescribe an optimal set of rules of the form ‘Stop after z days unless the catch exceeds $\phi(z)$ ’, where $\phi(z)$ is such that $z = z^*(H(\phi(z)), z)$. That is, if the stock level inferred from the catch and effort so far is such that a higher effort level would be optimal, fishing should continue. This analysis also applies to multi-species fisheries. The same solution can, in principle, be applied in fisheries with multiple users. As observed above, however, there are practical difficulties in achieving the precise monitoring of effort required to make such a solution work well.

References

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