Economics of Exhaustible Resources: The Fishery

Writers in the economic theory of fisheries have been primarily concerned with the characteristics of common-property resources. Such resources, where ownership is not perfect, are often over-exploited since free access allows excessive entry of labour and capital into the industry. In his initial articles Gordon [4], [5] argued that this entry would continue until all 'rent' from the fishery was dissipated. The problem for policy-makers has thus been to devise methods to correct this misallocation of resources. Accordingly, economic theory has concentrated on the equilibrium levels of effort in a fishery, the optimum level of effort, and methods to achieve this optimum either by capturing the rent in the form of taxes or by initiating some form of sole ownership.

Over-emphasis on these aspects of the fishing industry has led to the relative neglect of the bio-economic characteristics of the industry. Firstly the problem of determining the optimum time at which to exploit the fish during their life span has been given little serious consideration. Turvey [14] dealt with this problem of eumetric fishing as one aspect of sub-optimization within the industry. Others have considered it as a minor element in the problem of overfishing. However, as Pontecorvo [9] has argued, regulations specifying the size of capture are far more important than regulations determining the optimum level of effort: as long as effort is restricted to the larger fish, no amount of fishing effort can destroy a fishery.

Secondly, economists have not been critical of the type of growth function used in bio-economic models. Since Schaeffer [10], in correcting an error in Gordon, pointed out that population growth rate can be approximated by a quadratic function, it has been customary to use a growth function of the form:

$$dN/dt = aN - bN^2 - Y,$$

where dN/dt is the rate of change of population, N is the number in the population and Y is the yield or catch rate. Plourde [7], [8] and Smith [12], [13], for example, follow this method. Such a function is very restrictive. It states that the increase in population is a result of natural increase less both natural mortality and the catch rate.

This implies that there is no interaction between catch and natural mortality, indicating that fish not caught in period t are available in period $t+1$. This is a proposition which is not true in general. It can be argued that models which do not make explicit allowance for natural mortality and growth are inadequate for dealing with problems of eumetric fishing. There are many biological models relevant to the analysis. The method chosen here is the Beverton and Holt procedure of working on a year-class throughout its life span.

The approach adopted emphasizes the relationship between mining an exhaustible resource and exploiting a year-class (the recruits into a fishery in any particular year) over its life span. Due to natural mortality a year-class is eventually exhausted regardless of the extent of exploitation by man. The problem is to determine the rate of exploitation of a resource which is itself variable over time. The purpose of the present article is to examine this question by considering the fishery as a problem in optimal control of an exhaustible resource.

A Theory of Exhaustible Resource

Assume that the contents of a mine are to be extracted over a period of time (0 to T) in such a way that the present value of the mine is maximized. This problem has been dealt with by Hotelling [6], although his model is not readily applicable to fishing. The model has been reformulated here to enable its application to the fishing industry. That is, maximize:

$$\int_0^T \pi\ (q,t)e^{-rt}dt \tag{1}$$

subject to

$$\dot{K} = -q(t) \tag{2}$$

$$K \geq 0$$

$$q \geq 0,$$

where π is the value of the mine to society, r the instantaneous rate of interest, $\dot{K}$ the rate of change of the contents of the mine, and $q(t)$ the quantity extracted in each period.

Now π is a function of the net price, $p(t)$, received per unit of resource and $p(t)$ will vary with $q(t)$. Assume (omitting t when it occurs as an argument):

$$p = f(q), \text{ and } f'(q) < 0$$

$$\pi = \int_0^q p\ dq. \tag{3}$$

The necessary condition for a solution (see Arrow and Kurz [1, p. 48]) is the existence of a continuous function ψ such that:

$$L = \pi - \psi q + \lambda_1 K + \lambda_2 q \tag{4}$$

$$\partial L/\partial q = 0;\ \text{thus } \partial\pi/\partial q = p = \psi - \lambda_2 \tag{5}$$

$$\begin{aligned} \dot{\psi} &= r\psi + \lambda_1, \\ \lambda_1 &\geq 0;\ \lambda_1 K = 0 \\ \lambda_2 &\geq 0;\ \lambda_2 q = 0 \\ \lim_{t\to T} e^{-rt}\psi K &= 0;\ \lim_{t\to T} e^{-rt}\psi \geq 0. \end{aligned} \tag{6}$$

When $K > 0, \lambda_1 = 0$; and from (6), $\dot{\psi}/\psi = r$.

When $q > 0, \lambda_2 = 0$; and from (5), $p = \psi$.

Hence $\dot{p}/p = r$.

This requires net price to rise at the rate of r per cent. By equation (3) quantity extracted must fall over time.

A Theory of Eumetric Fishing

Beverton and Holt [2] popularized the concept of an optimum size at which fish should be caught. The argument can be outlined as follows. Over time each year-class decreases in numbers due to various factors affecting natural mortality. Simultaneously the surviving individuals in the class increase in weight. Consequently there will be a point in time when the biomass is at a maximum. A fishing method sufficiently selective to take fish in the size range corresponding to this maximum would maximize the yield from that year-class.

The technical and biological assumptions behind this theory are well known. Firstly, the theory can only be applied to species that are fished over their entire life span; this excludes migratory species such as tuna. Secondly, sufficiently selective gear must be available to operate within the optimum range. Thirdly, only one species can be fished at any time; otherwise the optimum mesh size is at best a compromise.

The economic objections to the theory have not been discussed adequately. The obvious objections are that costs and revenues are not considered. At any point of time large increases in catch may only be achieved with increasing marginal costs due to diminishing returns. Thus revenue and cost functions are important. Futher, the theory of eumetric fishing should be modified to allow for the cost of waiting. In other words, future yields must be discounted at some social rate of time preference. Scott [11, p. 44] has noted these points. The most important objection, however, is that the theory is static in the sense that it indicates that each year-class should be exploited at one point of time during its life span.

The following analysis suggests that it is best to exploit each year-class over a period of its life. The extent of exploitation will depend on the social rate of time preference, the rate of growth of the year-class, and the prevailing demand and cost conditions in the industry.

The problem is analogous to the mining example except that equation (2) must be altered to allow for changes in the resource itself. The rate of change of the stock of fish is determined by three factors: natural mortality, rate of catch and rate of growth.

Assume that natural mortality reduces the year-class according to an exponential decay law. The reduction will then be directly proportional to the biomass at that time. Let m be the instantaneous rate of natural mortality.

The growth factor will be determined by some biological growth function which will be a function of time. Normally the growth rate of an individual fish will rise, reach a maximum and then fall to zero. The weight of the fish will thus follow the standard sigmoid curve. Therefore, the effect on the biomass is given by $g(t)K$, where $g(t)$ is the growth function and K the biomass at that time.

The problem becomes one of maximizing:

$$\int_0^T \Pi e^{-rt} dt \tag{8}$$

subject to

$$\dot{K} = -q - mK + gK \tag{9}$$

$$K \geq 0$$

$$q \geq 0.$$

The necessary conditions are that there exists a $\psi(t)$ such that:

$$L = \pi - \psi(q + mK - gK) + \lambda_1 K + \lambda_2 q$$

$$\partial L/\partial q = p - \psi + \lambda_2 = 0 \tag{10}$$

$$\dot{\psi} = r\psi + \psi m - \psi g + \lambda_1 \tag{11}$$

$$\lambda_1 \geq 0; \ \lambda_1 K = 0 \tag{12}$$

$$\lambda_2 \geq 0; \ \lambda_2 q = 0 \tag{13}$$

$$\lim_{t \to T} e^{-rt}\psi K = 0; \ \lim_{t \to T} e^{-rt}\psi \geq 0.$$

Consider firstly the case where net price is independent of q so that p is constant. Given that $q > 0$, $K > 0$, so that $\lambda_1 = \lambda_2 = 0$. From (10) $p = \psi =$ constant, and from (11) $r + m - g = 0$ for optimization. This means that harvesting should be carried out in the period when the discounted value of the biomass is greatest (t^* in Figure 1). If the rate of interest is zero, we are reduced to the biologists' principle of harvesting when the biomass is greatest (t_{max} in Figure 1).

In the more general case of increasing costs, when $f'(q) < 0$

$$\dot{\psi}/\psi = r + m - g.$$

The relationship between r, m, g and ψ is illustrated in Figures 1 and 2. Figure 1 shows r, m and g as functions of t; Figure 2 shows ψ as a function of time. Thus the net price p must fall over time, reach a minimum, then rise. Since $p = f(q)$ and $f'(q) < 0$, optimal output should initially increase over time, until $t = t_m$, then fall until all fish are taken. Equations (10) and (13) place a restriction on the period over which the catch should be taken: if $p < \psi$, $q = 0$.

The mainspring of this analysis is that because of increasing costs and possibly falling prices as output is increased, the catch from any single year-class should be taken over several periods. There is no optimum time at which the fish should be caught, but rather an optimal time path.

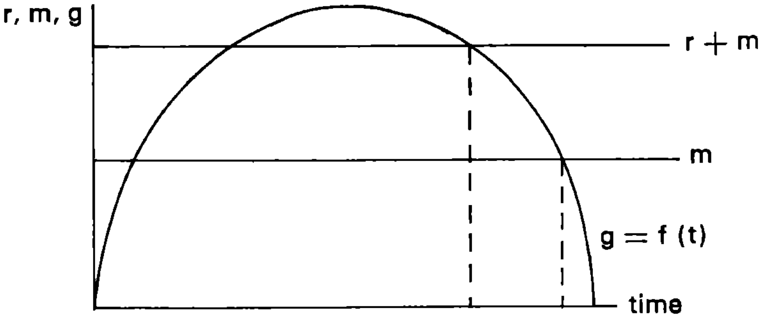

FIGURE 1

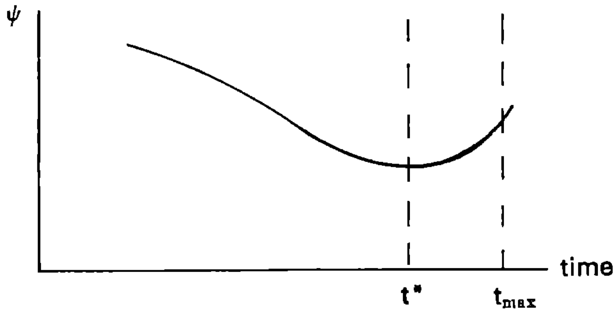

FIGURE 2

Implications for Theory and Policy

The method developed in this paper is an alternative theoretical approach to that adopted in the economic literature. By concentrating on the year-class, biological factors such as growth and natural mortality can be more easily integrated with economic factors. In particular it has been possible to outline the relationship between age of capture and economic efficiency. That age of capture can significantly affect the catch is exemplified by the North Sea plaice for which, had the age of first capture been 'increased from age three to age nine by increasing the mesh size of the trawls . . . the possible improvement would have been a doubling of catch for the same fishing intensity' [3, p. 97]. As emphasized above, however, the generally accepted doctrine in fisheries management, that there is one optimal age at which the biomass should be harvested, is not valid: rather there is an optimal time path.

The argument so far has assumed that it is possible to isolate a year-class in any fishery and keep it under surveillance for its life span. However, in a normal fisheries situation all year-classes are being exploited at any one time. Thus the year-class over its whole life span can be considered equivalent to the whole fishery at any point of time. Since for a year-class there is an optimal catch for each point of time, there must also be an optimum catch for each size or age in the whole fishery. Regulation should therefore aim at limiting, but not preventing, the catch from each age group. This could be achieved by licensing. This approach to the problem of fisheries management could be particularly important when one species is fished by different types of gear at different ages as, for example, when smaller fish are taken by trawling and larger by long-lining. The aim of management should be to maximize the present value of the year-class, which could require reallocation of catch between the two methods of fishing. It may even prove most efficient to take the complete harvest with one type of gear.

The analysis presented in this paper has primarily focused on one fundamental objective: the development of an integrated approach to problems of fisheries, combining the economic and biological variables relevant to the industry. With the increasing world demand for fish as a major source of protein and food supply and the need for efficient exploitation of this resource, it is suggested here that only within such a framework can a proper understanding of the problems of the management of fisheries be gained.

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REFERENCES

[1] Arrow, K. J. and M. Kurz, *Public Investment, the Rate of Return, and Optimal Fiscal Policy* (Johns Hopkins Press, Baltimore, 1970).
[2] Beverton, R. J. and S. J. Holt, *On the Dynamics of Exploited Fish Populations* (HMSO, London, 1957).
[3] Cushing, D. H., *Fisheries Biology: A Study in Population Dynamics* (University of Wisconsin Press, Madison, 1968).
[4] Gordon, H. S., 'An Economic Approach to the Optimum Utilization of Fishery Resources', *Journal of Fisheries Research Board of Canada*, 1953, pp. 442-57.
[5] ———, 'The Economic Theory of a Common Property Resource: The Fishery', *Journal of Political Economy*, Vol. 62, April 1954, pp. 124-42.
[6] Hotelling, H., 'The Economics of Exhaustible Resources', *Journal of Political Economy*, Vol. 39, April 1931, pp. 157-75.
[7] Plourde, C. G., 'A Simple Model of Replenishable Natural Resource Exploitation', *American Economic Review*, Vol. LX, June 1970, pp. 518-22.
[8] ———, 'Exploitation of Common-Property Replenishable Natural Resources', *Western Economic Journal*, Vol. 9, September 1971, pp. 256-66.
[9] Pontecorvo, G., 'Optimization and Taxation on an Open-Access Resource: The Fishery', in M. Gaffney (ed.), *Extractive Resources and Taxation* (University of Wisconsin Press, Madison, 1967), pp. 157-67.

[10] Schaeffer, M. B., 'Some Considerations of Population Dynamics in Relation to the Management of the Commercial Marine Fisheries', *Journal of Fisheries Research Board of Canada,* September 1957, pp. 669-80.
[11] Scott, A. D., 'The Economics of Regulation of Fisheries', in R. Hamliseh (ed.), *Economics of Fishery Regulation* (F.A.O., Rome, 1962), pp. 25-61.
[12] Smith, V. L., 'Economics of Production from Natural Resources', *American Economic Review,* Vol. LVIII, June 1968, pp. 409-31.
[13] ———, 'On Models of Commercial Fishing', *Journal of Political Economy,* Vol. 78, April 1970, pp. 181-98.
[14] Turvey, R., 'Optimization and Suboptimization in Fishery Regulation', *American Economic Review,* Vol. LIV, March 1964, pp. 66-76.