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I. An Industry Model with Externalities

Commercial fishing is characterized by three key economic and technological features that are relevant to the formulation of an economic theory of fish production.

1. A fishery resource, although conceivably exhaustible, is replenishable; that is, it is subject to laws of natural growth which define an environmental biotechnological constraint on the activities of the fishing industry.

2. The resource and the activity of production from it form a stock-flow relationship. The new growth in the population fish mass depends upon the harvest rate relative to natural recruitment to the stock. If the harvest rate exceeds the recruitment rate, the stock declines, and vice versa.

3. The recovery or harvesting process is subject to various possible external effects all of which represent external diseconomies to the firm: (*a*) Resource *stock externalities* result if the cost of a fishing vessel's catch decreases as the population of fish increases. (*b*) *Mesh externalities* result if the mesh size (or other kinds of gear selectivity variables) affects not only the private costs and revenues of the fisherman but also the growth behavior of the fish population. (*c*) *Crowding externalities* occur if the fish population is sufficiently concentrated to cause vessel congestion over the fishing grounds and, thus, increased vessel operating costs for any given catch. All of these various types of externalities arise fundamentally because

The preparation of this paper was supported by National Science Foundation grant GS-1835 to Brown University. It is one of a series of papers dealing with the economics of production from extractive natural resources (Smith, 1968). I am indebted to Anthony Scott for many helpful comments on an earlier draft.

of the "common property," unappropriated (Gordon, 1954; Scott, 1955) character of most fishery resources, especially ocean and large lake fisheries.

The literature of fishing economics has drawn attention, in some form, to each of these characteristics, and has initiated the development (Crutchfield and Zellner, 1962) of a formal dynamic industry model of the productive process and the interaction of the exploiting industry with the exploited population. But there seems to be a need for generalization, explication, and integration of this previous work. Toward this end we will treat the case of a homogeneous industry composed of K identical fishing vessels or firms, each producing at a catch rate x pounds per unit time. The total harvest rate is then Kx.

The purpose of the model is to provide one example of a descriptive theory that transforms any specific pattern of assumptions about cost conditions, demand externalities, and biomass growth technology into a pattern (conceivably observable) of exploitation. The model or variations on it would appear to have much wider possible applications, such as (1) a theory of bionomic equilibrium in primitive hunter cultures and (2) possibly the rudiments of an economic theory of species extinction, both historical and modern.

We consider a single fish species with population mass X in pounds. In the absence of predation by man, following Lotka (1956) (see also Christy and Scott, 1965, pp. 7–8, 81), we assume a recruitment rate or growth function $dX/dt \equiv \dot{X} = f(X)$. We posit that $f(X)$ has the properties $f(\underline{X}) = f(\overline{X}) = 0, f'(X^{\circ}) = 0, f''(X) < 0, X \geq 0, 0 \leq \underline{X} < X^{\circ} < \overline{X}$. The equilibrium population in the natural state is $\overline{X}$, and populations below $\underline{X}$ are assumed not to be viable because of vulnerability to disease, parasites, or predators, or to inadequate fecundity. By setting $\underline{X} = 0$ we get the special case when such considerations are not relevant. The solution to the differential equation $\dot{X} = f(X)$ provides the law of growth for the species. When $f(X)$ is quadratic the result is the popular logistics law of growth (Lotka, 1956, pp. 64–66). For individual fish the empirical law of growth is an asymmetrical sigmoid curve with the inflection point at a weight below one-half the asymptotic weight (Beverton and Holt, 1957, pp. 31–35, 96–135). However, there is experimental evidence to suggest that some life forms follow the logistics law in a constant trophic environment. By postulating $f(X)$, without any attempt to deal analytically with the components of mass growth—the birth process, individual member growth, death and capture processes—we are electing to take an aggregative approach to the biotechnology. Beverton and Holt (1957, pp. 329–30) have discussed the function and limitations of such a "sigmoid curve" theory of population growth.

When the population is exploited by a fishing industry employing mesh size m so that harvesting is confined to those members whose size is not below m, a natural generalization of the growth hypothesis is[1]

$$\dot{X} = f(X, m, Kx). \tag{1}$$

In (1) I assume that $f(X, m, Kx)$, as a function of X for any given m and Kx, exhibits the inverted "U" properties specified above. Figure 1 provides an illustrative mapping of the recruitment function. Also in (1), it will be assumed that $f_3 < 0$, that is, any increase in harvest will lower net recruitment. In general, we assume an interaction between the harvest and the productivity of the stock. If there is no interaction, then $\dot{X} = f(X, m) - Kx$; that is, an additional ton of catch reduces instantaneous growth by a ton.

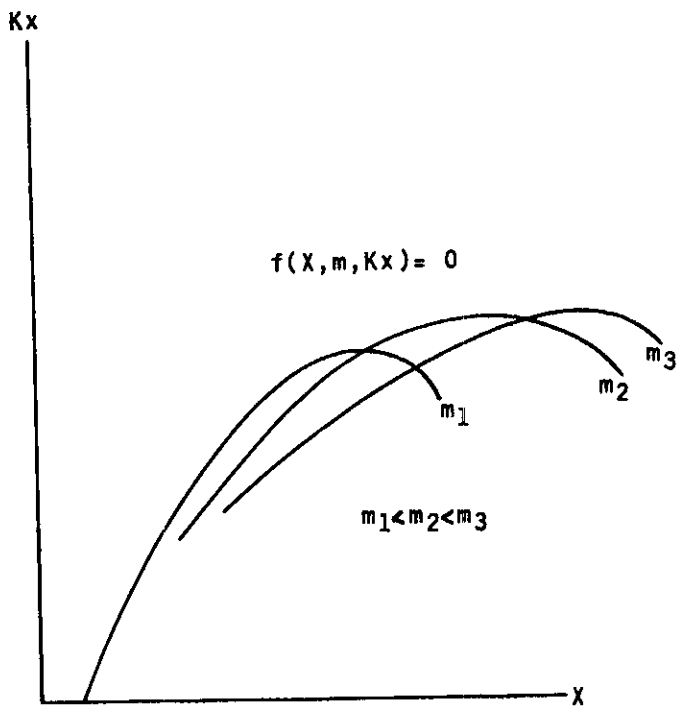

FIG. 1

[1] Various special forms of such a recruitment-rate function are implicit in the fishing literature. All treatments known to me assume steady-state conditions ($\dot{X} = 0$). Thus, in Gordon's (1954) pathbreaking analysis of "bionomic" equilibrium, the harvest is assumed to depend upon population size and "fishing effort," E, or $Kx = F(X, E)$ in my notation. His model further assumes that population declines with harvest, $X = X(Kx)$. Turvey (1954), dealing with the economics of mesh control, assumes $Kx = F(E, m)$, in my notation. Turvey follows Beverton and Holt (1957) in assuming that population size does not interact with fishing effort in determining the harvest rate (or total fishing mortality) under steady-state conditions. I dispense with any use of the concept of "fishing effort," since it is adequately and more familiarly measured by operating cost. All the above authors assume $C = C(E)$—cost is an increasing function of effort.

The most general hypothesis governing the long-run operating costs of a fishing vessel must account for both stock and crowding externalities. If we let $\hat{\pi}$ be the minimum rate of profit required to hold a vessel in the industry, then total cost per unit time is assumed to be given by $C = \phi(x, X, m, K) + \hat{\pi}$ for an individual fisherman and fishing vessel. Given the size of the fish population, mesh size, and number of vessels, cost increases with the vessel catch rate, x. Similarly, for any given catch rate, mesh size, and industry size, cost decreases with X. A *ceteris paribus* increase in mesh size is assumed to require fishing "effort" (in particular, the number of a vessel's netting motions, due to escapement), and therefore costs, to increase if the same weight of catch is to be maintained. Thus, m enters as a private cost factor in ϕ. As an externality it enters indirectly via equation (1). Finally, an increase in the size of the industry, with x, X, and m fixed, will increase each vessel's operating costs due to crowding. Either of the externality variables K or X may be absent from the cost function in particular fisheries. Crowding may only rarely be a factor, and for some species cost may not be affected significantly by population size. Where population size is very large relative to the industry, resource stock externalities are likely to be negligible. Hence, we assume that $\partial C/\partial x \equiv C_1 > 0$, $\partial C/\partial X \equiv C_2 \leq 0$, $\partial C/\partial m \equiv C_3 > 0$, $\partial C/\partial K \equiv C_4 \geq 0$.[2]

Industry revenue $R(Kx, m)$ is assumed to depend upon both the harvest Kx and the mesh size m used by all K vessels in the industry.[3] Increases in m, for a given harvest, raise the average size of fish caught. The result will be an increase in revenue for a species whose larger members are in demand, while revenue will decrease if only the smaller members are desired. Hence, profit for the individual fisherman can be written $\pi = p(m)x - C(x, X, m, K)$, where $p(m) = [R(Kx, m)]/(Kx)$. We assume that the individual fisherman desires to maximize this profit, but that he perceives only x and m as decision variables, with x not affecting price. His price may be affected by m because species size is priced as a quality in the market very much as "long grain" and "short grain" rice bring different prices to the competitive rice farmer. Thus, for given m, the individual fisherman perceives a fixed price $p(m) = [R(Kx, m)]/(Kx)$ at which he can sell unlimited quantities of fish, x, giving him a revenue $p(m)x$. His profit-maximizing decision rules are therefore

$$p(m) \equiv \frac{R(Kx, m)}{Kx} = C_1(x, X, m, K), \tag{2}$$

$$p'(m)x \equiv \frac{R_2(Kx, m)}{K} \leq C_3(x, X, m, K), \text{ if } < m = \underline{m}. \tag{3}$$

[2] Anthony Scott has called my attention to the possibility that $C_4 < 0$. If more vessels make it easier to find fish, then fish discovery appears as an external economy.

[3] For simplicity it is assumed that all vessels use the same size mesh, whereas in practice, for some species, different vessels might specialize in the capture of different sizes of fish. A treatment of this case would require a relaxation of the assumption that firms are identical.

Condition (2) requires the perceived price to equal marginal catch cost, and (3) requires the marginal revenue from varying the composition of the catch (mesh) to equal its marginal cost. If in the latter case marginal cost exceeds marginal revenue at the maximum, then $m = \underline{m}$; that is, we make mesh as small as possible.

In Figures 2 and 3 we illustrate possible partial equilibrium solutions for $m = m^o$. In Figure 2 $p'(m)$ is assumed to be positive, and above $C_3(x^o, X^o, m, K^o)$, for some values of $m > \underline{m}$, with (x, X, K) given. We have then a unique optimal mesh size $m^o > \underline{m}$ for each fisherman. Figure 3 illustrates the case in which each fisherman has no private incentive to harvest only the older and larger members of the species and proceeds to use the smallest practicable mesh size, which is, by definition, $\underline{m}$.

Finally, we assume free entry (and exit) in proportion to profit (and loss), with the exit-speed coefficient not necessarily equal to the entry-speed coefficient. That is, letting $dK/dt \equiv \dot{K}$, we have

$$\dot{K} = \begin{cases} \delta_1 \pi, \text{ if } \pi \geq 0, \\ \delta_2 \pi, \text{ if } \pi < 0, \end{cases} \tag{4}$$

with $\delta_1 \geq \delta_2$, so that vessels might enter the particular fishery in response to profit at a more rapid rate than they would leave in response to loss. This would be the case if vessels were relatively specialized and durable. On the other hand, if fishing vessels can easily be used for the capture of other species, or even for non-fishing activities, then we might have $\delta_1 = \delta_2$.

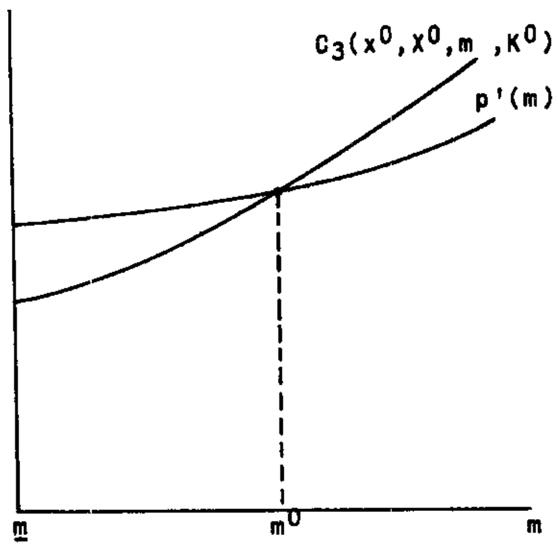

FIG. 2

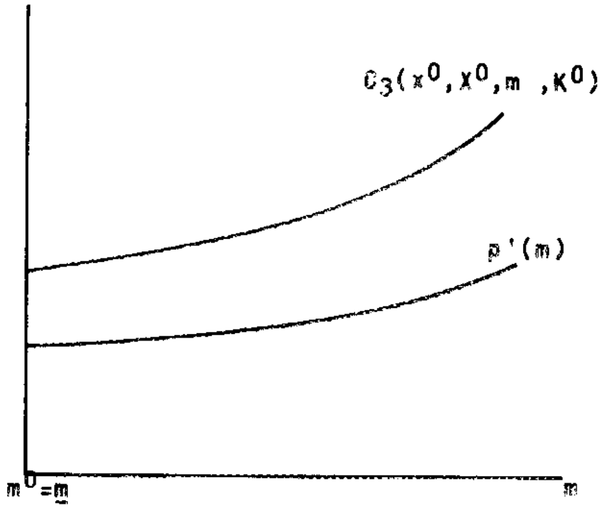

FIG. 3

If we assume further that equations (2) and (3) together provide unique values of x and m for every (X, K) pair, the system (1)–(4) reduces to two non-linear first-order differential equations:

$$\dot{X} = F(X, K), \tag{5}$$

$$\dot{K} = I(X, K). \tag{6}$$

When $\dot{X} = 0$, (5) defines those combinations of (X, K) that produce ecological equilibrium between the fish mass and the exploiting industry. When $\dot{K} = 0$, (6) defines those combinations of (X, K) that produce equilibrium between the exploiting industry and alternative uses of capital in the economy as a whole.

The system (1)–(4) assumes a single large fishery exploited by a competitive industry. A special case of this system occurs when there are numerous fisheries in a competitive world and price can be regarded as given to the individual fishery. Then, the profit function is again $\pi = p(m)x - C(x, X, m, K)$, but now Kx is total output from an individual fishery and $p(m)$ is the world price independent of the output of any one fishery. In this case, corresponding to (1)–(4):

$$\dot{X} = f(X, m, Kx), \tag{1'}$$

$$p(m) = C_1(x, X, m, K), \tag{2'}$$

$$p'(m)x \leq C_3(x, X, m, K), \quad \text{if } <, \quad \text{then } m = \underline{m}, \tag{3'}$$

$$\dot{K} = \begin{Bmatrix} \delta_1\pi, & \text{if} \quad \pi \geq 0 \\ \delta_2\pi, & \text{if} \quad \pi < 0 \end{Bmatrix}. \tag{4'}$$

II. A Quadratic Illustration

The above model is not mathematically simple. It is very rich in possible solutions, given only the stated qualitative restrictions on the cost, revenue, and recruitment rate functions. This can be demonstrated clearly in a very simple illustration which assumes no crowding externalities and which abstracts from mesh size considerations.

Assume a quadratic total revenue function, $R(Kx) = (\alpha - \beta Kx)Kx$, with $\alpha, \beta > 0$, and a quadratic recruitment rate function, $f(X) = (a - bX)X$, with $a, b > 0$. Notice that we have $\underline{X} = 0$, $\overline{X} = a/b$, $X^\circ = a/(2b)$. Finally, let total cost be $C = [(\gamma x^2/X) + \hat{\pi}]$, with $\gamma > 0$, $\hat{\pi} > 0$. The equation system corresponding to (1)–(4) becomes

$$\dot{X} = (a - bX)X - Kx, \tag{7}$$

$$\alpha - \beta Kx = \frac{2\gamma x}{X}, \quad \text{or} \quad x = \frac{\alpha X}{2\gamma + \beta KX}, \tag{8}$$

$$\dot{K} = \begin{cases} \delta_1 \pi, & \pi \geq 0 \\ \delta_2 \pi, & \pi < 0 \end{cases} \quad \pi = (\alpha - \beta Kx)x - \frac{\gamma x^2}{X} - \hat{\pi}. \tag{9}$$

With $\dot{X} = 0$, equations (7) and (8) define the resource stock equilibrium curve $F(X, K) = 0$ shown in Figure 4. With $\dot{K} = 0$, (8) and (9) define the industry investment equilibrium curve $I(X, K) = 0$ in the same figure. The

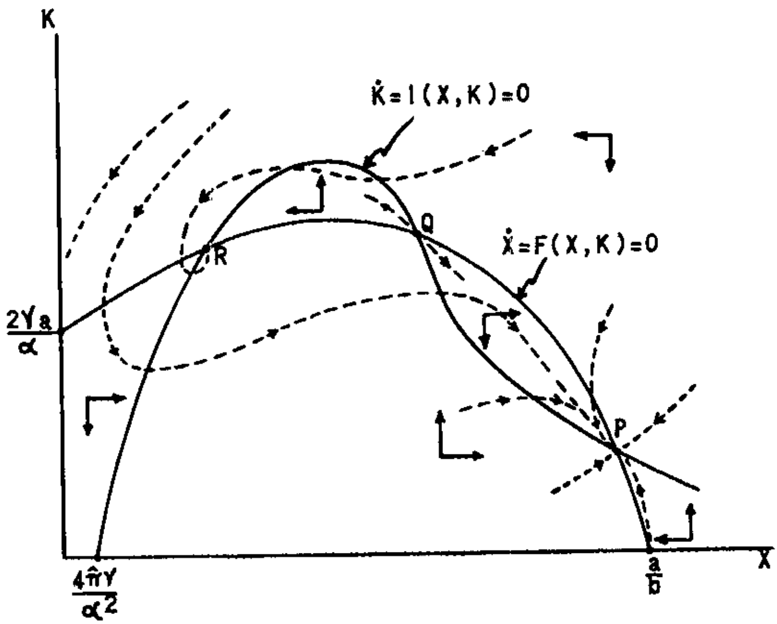

FIG. 4

directions of motion of a point in phase space (X, K) are indicated by the perpendicular arrows in the six partitions of the non-negative quadrant that are formed by the two curves. Points above the fishery resource equilibrium curve represent states in which the total harvest exceeds the recruitment of new stock, causing a net decline in the stock, while points below correspond to states in which recruitment exceeds the harvest, causing the fish stock to rise. Points above the industry investment equilibrium curve are states in which profits are negative, causing an outflow of capital (if $\delta_2 > 0$) from the industry, while points below represent states of positive profit, causing an inflow of capital into the industry.

The dashed curves in Figure 4 illustrate various possible dynamic paths in phase space on the assumption that $\delta_1 = \delta_2$. Beginning at any initial point $[K(0), X(0)]$ on such a path, the system moves along the path in the direction indicated. Thus, if $K(0) = 0$, $X(0) = a/b$, corresponding initially to an unexploited fishery and non-existent fishing industry, investment and the fish population mass move along the indicated path to the stationary stable equilibrium, point P. Another stable equilibrium point is illustrated by R, toward which convergence is along a cyclical path while Q is an unstable equilibrium.

Figure 5 illustrates a case with a single equilibrium point in the positive quadrant. The path OST is intended to illustrate a possible dynamic path with $\delta_1 = \delta_2 > 0$, while OST' is a possible outcome if $\delta_1' = \delta_1 > \delta_2' > 0$.

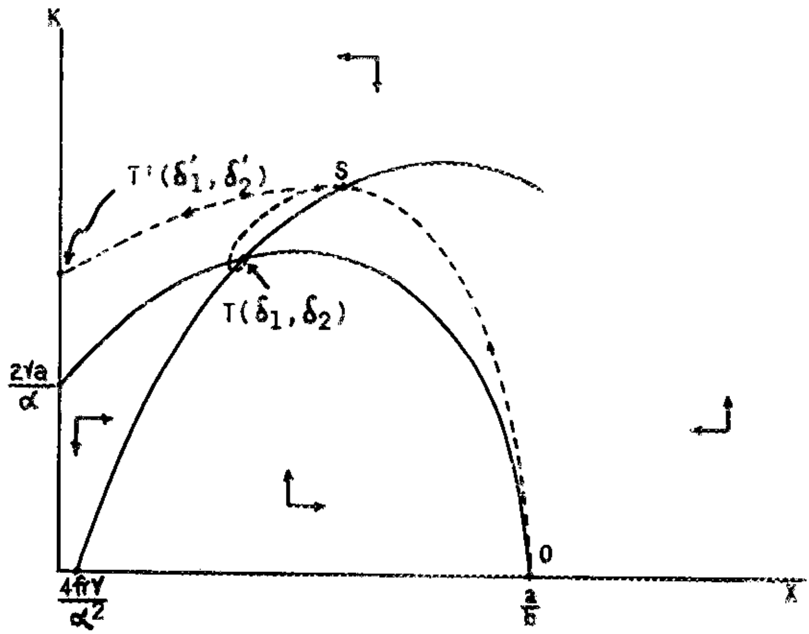

Fig. 5

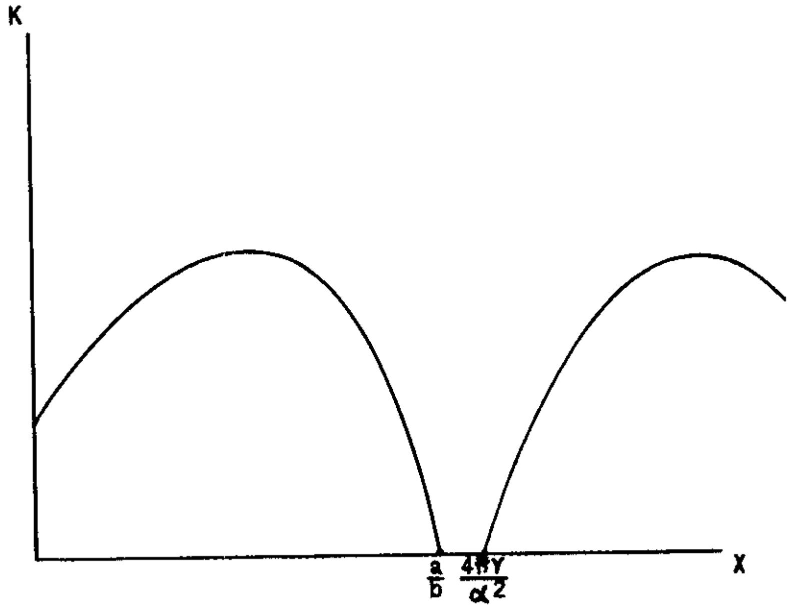

FIG. 6

Figure 6 illustrates a case in which $a/b < (4\hat{\pi}\gamma)/\alpha^2$, and exploitation of the fishery is not economically viable. This results from a combination of relatively (i) low market value (α), (ii) high required rate of return on vessels ($\hat{\pi}$) (as, for example, might occur if risks are unusually high), (iii) high operating costs (γ), or (iv) low natural-state population mass (a/b). This set of conditions is, of course, the most common case, since the overwhelming majority of ocean and freshwater animal species are not commercially recoverable.

III. Sole Ownership or Right of Access to a Fishery

For purposes of contrast and comparison with decentralized competitive exploitation, consider next the case of a fishery exploited by a sole owner or a firm to whom an exclusive right of access has been granted. Although such a state is rare in modern capitalistic societies, it was and is very common, where feasible, in societies judged to be more "primitive."

Indeed, Gordon (1954, p. 134) reports that common tenure is very rare even in hunting societies, and then only in those cases where the hunted resource is migratory over such a large area that it becomes unfeasible for the society to regard the resource as husbandable. Apparently, the "invisible hand" has an ancient history of endowing societies with an economic wisdom in traditions of fisheries resource utilization that have not always been continued in modern societies.[4]

Whatever may be the proper interpretation of anthropological data on the granting of property rights, the economic function of such rights is clear: The appropriation of a resource by a sole owner, or its legal equivalent, internalizes or "privatizes" the social costs associated with the three types of externalities discussed above.

Consider a sole owner exploiting a single fishery that is small in relation to the world supply, so that price $p(m)$ is given to the fishery. His profit is $\pi = p(m)Kx - KC(x, X, m, K)$, which he desires to maximize with respect to the choice of (x, m, X, K) subject to the constraint $f(X, m, Kx) = 0$. The Lagrange function is then $\phi = p(m)Kx - KC(x, X, m, K) + \lambda f(X, m, Kx)$, and the first-order conditions for a constrained maximum can be put in the form

$$p(m) = C_1 - \lambda f_3, \tag{10}$$

$$xp'(m) + \frac{\lambda f_2}{K} \leq C_3, \quad \text{if} <, \text{then} \quad m^o = \underline{m}, \tag{11}$$

$$\lambda = \frac{KC_2}{f_1}, \tag{12}$$

$$\frac{\pi}{K} = p(m)x - C = KC_4 - \lambda f_3 x, \tag{13}$$

$$f(X, m, Kx) = 0. \tag{14}$$

The Lagrange multiplier, λ, is the marginal profitability of recruitment. The marginal profitability of the fleet harvest is $-\lambda f_3$, which, in profit equilibrium, must equal the marginal "social" cost of the harvest, $(KC_2 f_3)/f_1$, due to resource stock externalities, from (12). The term "social" cost refers to costs external to the individual vessels and therefore external to decentralized competitive firms, but of course they are private "user" costs to the sole owner. Condition (10), in the form $p(m) = C_1 - (KC_2 f_3)/f_1$, requires the vessel catch rate to be adjusted until price equals direct plus user catch cost. Condition (13) requires the net marginal direct return on investment in a vessel, $p(m)x - C$, to equal the marginal social cost, $KC_4 - (KC_2 x f_3)/f_1$, of adding the vessel to the fleet. The term KC_4

[4] However, no such economic wisdom is apparent during the Pleistocene period in the husbanding of those native North American mammals whose adult body weight exceeded one hundred pounds. Some 70 per cent of all such species (mammoth, mastodon, horses, camels, ground sloths, oxen, antelope, saber-toothed tiger, giant beaver, and so on, totaling over one hundred species) became extinct during a period of only one thousand years following the arrival of the Paleo-Indians about twelve thousand years ago. For a forceful marshaling of evidence in favor of the hypothesis that man, through the use of fire, the stone-tipped spear, and the communal hunting party, succeeded in a gigantic "overkill" of these megafauna, see Martin (1967).

reflects external costs due to crowding, while $-(KC_2xf_3)/f_1$ reflects catch externalities by the additional vessel. Finally, (11) requires the marginal private plus social revenue from mesh adjustment (varying catch composition) to not exceed the (private) cost of the adjustment. The term $\lambda f_2/K = (C_2f_2)/f_1$ measures social gains (savings in external catch costs) produced by an increase in mesh size, which in turn increases population recruitment.

IV. Competitive versus Centralized Recovery

By comparing the system (1′)–(4′), $\dot{X} = \dot{K} = 0$, with (10)–(14), it is seen that the conditions governing exploitation under the competitive and centralized organizations are the same except for the above social costs. Several propositions follow from such a comparison.

Note first that the sole owner will never deplete a fishery to a population mass at which $f_1 > 0$; that is, in Figure 1, for an optimal mesh, he will always operate to the right of the maximum sustainable yield point. To prove this, assume the contrary and let the system (10)–(14) be satisfied by a point (x^*, X^*, m^*, K^*) with $f_1(X^*, m^*, K^*x^*) > 0$. Then from the properties of the function f, there must exist an $X^{**} > X^*$ such that $f(X^*, m^*, K^*x^*) = f(X^{**}, m^*, K^*x^*) = 0$, and $f_1(X^{**}, m^*, K^*x^*) < 0$. But since $C_2 < 0$, it follows that the point (x^*, X^{**}, m^*, K^*) produces the same total catch, satisfies the constraint (14), and provides a larger profit. Profit cannot be a maximum unless $f_1 < 0$. Hence, from (12), $\lambda > 0$.

Second, under sole ownership, a pure profit or rent is provided by the fishery: Since $C_4 > 0$ and $\lambda f_3 < 0$, from (13) we must have $\pi > 0$ in equilibrium. This positive rent would eventually be absorbed in higher costs by free entry under a competitive organization of production.

The literature of fishery economics contains several discussions of the effect of competition versus sole ownership on capital requirements and output (or sustainable yield) in the stationary state. Thus, Gordon (1954, p. 141) states, "The uncontrolled (competitive) equilibrium means a higher expenditure of effort, higher fish landings, and a lower continuing fish population than the optimum [sole ownership]." Christy and Scott (1965, p. 9) say, "Eventually [under competition], the fishery may arrive at an equilibrium . . . which is likely to be marked by a relatively large amount of effort, a low population, and a low sustainable yield," as contrasted with sole ownership. Also (*idem*) "There will tend to be an excessive amount of capital and labor applied to the fishery."

It does not follow from the models of the present paper that capital requirements are greater or that output (sustainable yield) is unambiguously either larger or smaller under competition than under sole ownership. This is best demonstrated by a counterexample. Consider a simple case of the above models in which $f_2 \equiv C_3 \equiv C_4 \equiv 0$ and $\dot{X} = f(X) - Kx$

(no mesh or crowding externalities). Also assume that the output capacity of each vessel is fixed (for example, marginal operating cost might be constant up to some capacity limit), say $x = \bar{x}$, and that $\delta_1 = \delta_2 = \delta$. Then the cost function for a vessel is $C(\bar{x}, X)$ and exploitation is defined by $\dot{X} = f(X) - K\bar{x}$ and $\dot{K} = \delta[p\bar{x} - C(\bar{x}, X)]$. At a stationary equilibrium,

$$p\bar{x} = C(\bar{x}, X^*), \tag{15}$$

$$K\bar{x} = f(X^*), \tag{16}$$

where X^* is the unique fish population at which the industry is just normally profitable. The heavy-lined curves of Figures 7 and 8 illustrate the functions (15) and (16) in phase space and an equilibrium of both population and capital investment at (X^*, K^*).

The sole owner's profit function is $\pi = pK\bar{x} - KC(\bar{x}, X)$, and his static equilibrium is defined by

$$K\bar{x} = \frac{(p\bar{x} - C)f'}{C_2}, \tag{17}$$

$$K\bar{x} = f(X), \tag{18}$$

where (17) is implied by the first-order conditions for a constrained maximum. In this model, comparing the two systems of production

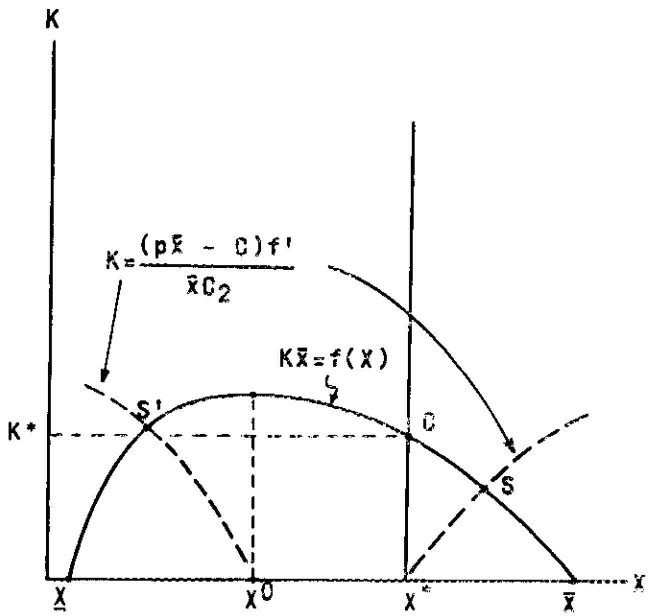

FIG. 7

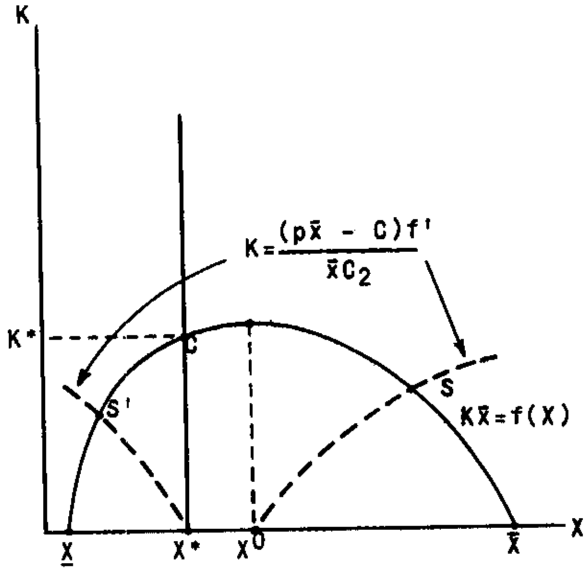

FIG. 8

organization becomes a matter of comparing equations (15) and (17). In Figures 7 and 8 the dashed lines through S and S' represent, in general, the function (17) on the assumptions $C_2 < 0$, $C_{22} > 0$ and the previously stated properties of $f(X)$.

Thus, in Figure 7 is depicted a competitive solution with $X^* > X^\circ$ and a sole owner's maximum at S. To show why, we compute

$$\bar{x}\frac{dK}{dX} = \frac{(p\bar{x} - C)f''}{C_2} - f' - \frac{(p\bar{x} - C)f'C_{22}}{(C_2)^2} \tag{19}$$

and observe from (15) that $p\bar{x} - C \lesseqqgtr 0$ according as $X \lesseqqgtr X^*$. Now, if $\underline{X} \leq X < X^\circ$, then $p\bar{x} - C < 0, f' > 0$, and it follows from (17) and (19) that $K\bar{x} > 0$ and $\bar{x}(dK/dX) \lesseqqgtr 0$, as shown by the dashed curve through S' in Figure 7. At $X = X^\circ, p\bar{x} - C < 0, f' = 0$, and $K\bar{x} = 0, \bar{x}(dK/dX) < 0$. For $X^\circ < X < X^*$, $K < 0$, so this segment of (17) is omitted in Figure 7. At $X = X^*$, $p\bar{x} - C = 0$ and $f' < 0$, and it follows that $K = 0$ and $\bar{x}(dK/dX) = -f' > 0$. Finally, on $X^* < X < \bar{X}, p\bar{x} - C > 0, f' < 0$ and $K > 0$, while $\bar{x}(dK/dX) > 0$, as shown by the dashed curve through S.

Similarly, in Figure 8, for $\underline{X} \leq X \leq X^*$, $K \geq 0$, and $\bar{x}(dK/dx) \lesseqqgtr 0$; for $X^* < X < X^\circ$, $K < 0$; and for $X^\circ \leq X < \bar{X}$, $K \geq 0$, $\bar{x}(dK/dX) > 0$, as indicated by the dashed lines. In both figures, point C represents the competitive equilibrium; S and S' represent points satisfying (17) and (18) for the sole owner, but only S can be a global maximum and therefore a profit equilibrium point. Comparing C and S in Figure 8, it is clear that the competitive equilibrium may require a larger or smaller amount of capital than sole ownership; also, the harvest, which is the same as the population yield ($K\bar{x}$), may be larger or smaller at C than at S. That point C may imply a smaller harvest (and capital requirements) than S is made obvious by the fact that we could choose $p\bar{x}$ so that X^* equals (or is near to) $\underline{X}$, where the competitive harvest is zero, yet $\bar{x}(dK/dX) > 0$, $K > 0$, for $X^\circ \leq X < \bar{X}$ so that at S, $K\bar{x} > 0$.

These results, insofar as they stand in contrast to the earlier literature, are due to the explicit hypothesis that population reduction increases operating cost, while at first increasing, then decreasing, sustainable yield.

V. Regulation of Competitive Recovery

An alternative to centralized management as a means of achieving efficient fishery production is to regulate appropriately the competitive process. This has been the attempt in practice. In theory the objective of regulation is to induce the decentralized competitive industry to behave like a sole owner. One way to achieve this is for the social costs appearing in the system of behavior equations (10)–(13) to be imposed by the regulating authorities upon the decision-making units of the industry. Equations (10)–(13) exhibit three kinds of social costs which must be reflected in each competitive fisherman's profit criterion: (i) A unit catch cost, $\lambda = KC_2/f_1$, reflecting the effect on fishing cost of a reduced population caused by an additional unit of catch. This social cost can be imposed on each fisherman by levying an extraction fee $U = -\lambda f_3$ on each pound of catch docked by a vessel. (ii) An annual vessel operating cost, KC_4, which measures the external crowding cost caused by an additional vessel in the industry. This charge is most easily levied by an annual license fee $L = KC_4$ on each operating vessel. (iii) Finally, as a control on mesh size, we impose a penalty cost, k, on the mesh employed by a vessel, where

$$k = \begin{Bmatrix} P, & \text{if} \quad m \lessgtr m^\circ \\ 0, & \text{if} \quad m = m^\circ \end{Bmatrix}.$$

The P is a fine large enough to dominate net revenue, so that it never pays the fisherman to choose $m \lessgtr m^\circ$, where m° is the optimal mesh satisfying the system (10)–(14).[5]

[5] It might be supposed that only a minimum mesh size restriction need be imposed, with a fine levied on the harvesting of smaller members of the population. In most cases this would probably be sufficient. However, for those species whose smaller members are prized, or whose medium-sized members are preferred by consumers, maximum or intermediate mesh restrictions would be in order. The strong-fine condition, k in the text, covers all these possibilities.

Hence, the individual fisherman's profit function for a vessel is $\pi = p(m)x - C(x, X, m, K) - Ux - L - k$, and the conditions for long-run industry equilibrium are

$$p(m) = C_1 + U, \tag{20}$$

$$m = m^{\circ}, \qquad k = 0, \tag{21}$$

$$\pi = p(m)x - C - Ux - L = 0, \tag{22}$$

$$f(X, m) = Kx. \tag{23}$$

In (20) each fisherman is assumed to adjust his catch rate until price equals marginal cost inclusive of extraction fees. Due to the high penalty for $m \lessgtr m^{\circ}$, m° is each fisherman's optimal mesh size. Equation (22) defines industry investment equilibrium when firms are subject to extraction and license fees. Hence, the equations for equilibrium of regulated competitive exploitation are the same as for the sole owner, (10)–(14), provided that $U = -\lambda f_3$ and $L = KC_4$ are fixed at optimizing values satisfying (10)–(14) and k has the form specified above (see Turvey, 1964).

VI. Comparison with Current Theory

Briefly stated, current fishing theory (Gordon, 1954, p. 136; Scott, 1955; Schaefer, 1957; FAO Fisheries Reports No. 5, 1962; Christy and Scott, 1965, chap. ii; Crutchfield, 1965) is as follows: Total cost for the industry is a function of fishing effort, $C = C(E)$. The sustainable yield or harvest by the industry, Y, is a function of effort, $Y = g(E)$. Total revenue is a function of yield, $R = R(Y)$. Hence, net return is

$$N = R(Y) - C(E) = R[g(E)] - C(E), \tag{24}$$

with effort E the only adjustment variable. Where mesh size is introduced as a decision variable (Turvey, 1964, pp. 66–67), it is assumed that $Y = g(E, m)$, that g has a maximum with respect to m for each E, and that revenue and cost are independent of m. Mesh size determination is then a separable suboptimization problem.

Often it is assumed that effort per fisherman is constant, so that total effort can be measured by the number of fishermen (K in my model). Net return is expressed as a function either of effort, as in (24), or of K. Figure 9 reproduces the diagram most often used as an illustration. That is, most authors assume constant long-run cost per fisherman so that C is proportional to E or K. Also, fish price is usually assumed to be constant, so that total revenue simply follows the inverted U-shaped sustainable yield curve. In Figure 9, the sole owner does not expand exploitation beyond OS, where net revenue is a maximum. Under decentralized, unregulated exploitation, the equilibrium effort or number of fishermen is at OD and all the rent of the fishery is absorbed in cost.

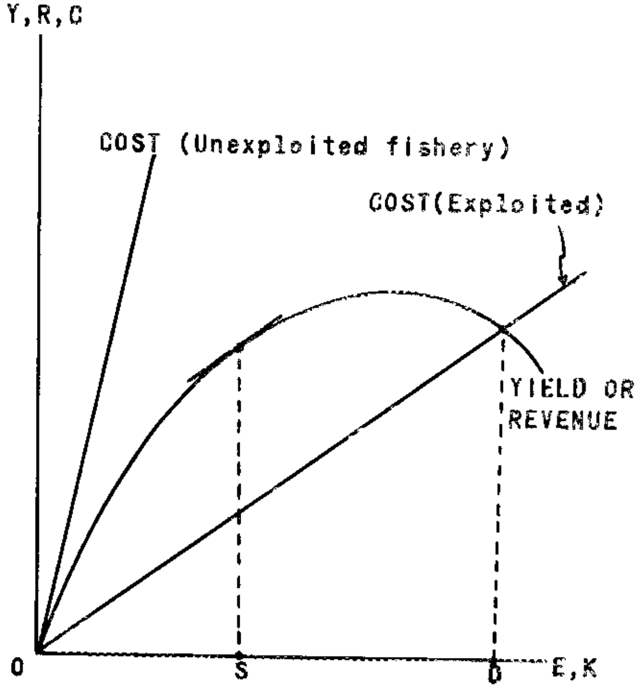

FIG. 9

This theory is able to account for the situation in which it is not commercially feasible to exploit a fishery; that is, cost may be everywhere above revenue for a particular species (see Fig. 9). However, it is not able to handle the situation in which a species may be depleted to the point of extinction. The theory implies that short of zero unit cost, the equilibrium yield to competitive exploitation is never zero with an extinct population. (Such a solution is possible in [1′]–[4′], for example, as in Figure 8 if $X^* < \underline{X}$.)

This is perhaps one of the more serious deficiencies in the received doctrine.[6] In addition, the standard analysis does not provide a dynamic theory;[7] it is not explicit about the various types of externalities that may

[6] If one believes in the boundless potential and inexhaustibility of the seas, then this is not a serious deficiency. But the myth of boundless potential, in my view, has been effectively destroyed by the arguments of Christy and Scott (1965)—in fact the present paper is in large measure an attempt to bring the economic theory of fishing into line with the persuasive arguments of their valuable and stimulating work.

[7] An important exception to this is to be found in the Mathematical Appendix to the book by Crutchfield and Zellner (1962, pp. 112–17). Their Appendix models are in the same dynamic spirit as those of the present paper, but use the quadratic form of the biological differential equation constraint such as I have used in the illustration

arise; nor does it explicitly distinguish the effect of such variables as vessel catch rate, fish population mass, investment, and mesh size.

The models developed in this paper can be adapted for purposes of comparison with Figure 9. Returning to the illustration used for the counterexample in Section IV, we have the vessel catch rate fixed, and total industry cost is $KC(\bar{x}, X)$. Total revenue is $R = pK\bar{x}$, and net revenue to the industry is

$$N = pK\bar{x} - KC(\bar{x}, X). \tag{25}$$

The conditions for maximum N to the sole owner are:

$$p\bar{x} = C + \frac{KC_2\bar{x}}{f'}, \tag{26}$$

$$K\bar{x} = f(X). \tag{27}$$

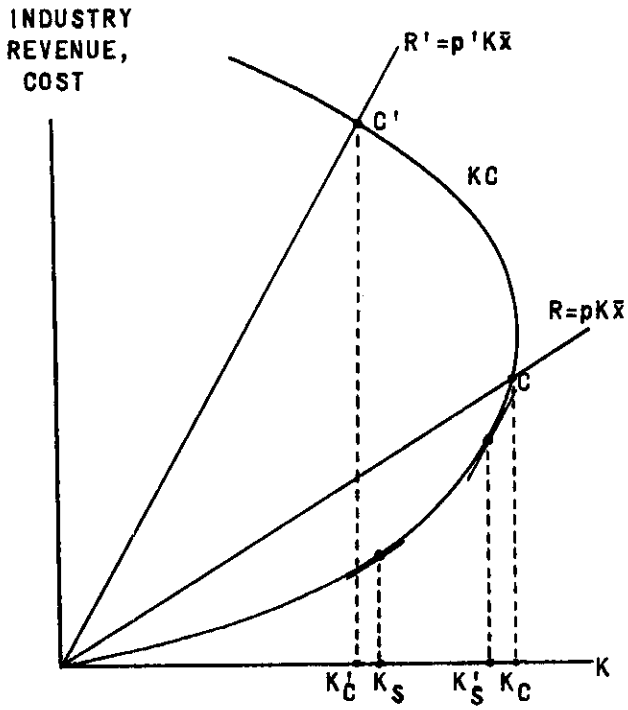

FIG. 10

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of Section II. The present paper generalizes their biological constraint, but more importantly, couples this constraint with a dynamic model of the exploiting industry. They also treat the problem of optimal fishery management over time, which I expect to consider in a separate paper.

Competitive equilibrium results when (25) and (27) are satisfied, with $N = 0$.

Figure 10 illustrates these solutions and provides the counterpart of Figure 9. Total revenue is proportional to fishermen (or the number of vessels). Total cost as a function of K only is determined simultaneously by $KC(\bar{x}, X)$ and condition (27). The slope of industry cost, in these terms, is $[d(KC)]/dK = [(KC_2\bar{x})/f'] + C$. Notice that the industry total-cost function does not have an inverse, because $f(X)$ does not. At price p the number of vessels operated by the sole owner is K_s, while the competitive industry operates $K_c > K_s$ vessels. If price is $p' > p$, as shown, the sole owner operates K_s' vessels, while $K_c' < K_s'$ are operated under competition. Under the assumptions of Figure 9, the theory of this paper implies *linear revenue* and *backward bending cost*, rather than linear cost and the humped revenue function of Figure 9.

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