NOT FOR QUOTATION

An Economic Theory of Common Property
Fishery Resources

by

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File Manuscript No. 66

July 1970

U.S. NATIONAL MARINE FISHERIES SERVICE
ECONOMIC RESEARCH DIVISION

AN ECONOMIC AND MANAGEMENT THEORY OF COMMON PROPERTY FISHERY RESOURCES

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ABSTRACT

A model of an economic theory of commercial fisheries is developed. The model integrates a biological growth model and a production function into a yield function for commercial fisheries. This function lays the basis for a supply function for commercial fishery products. A demand function is introduced and equilibrium conditions are discussed. In addition, schemes for management of a commercial fishery are discussed briefly.

INTRODUCTION

The economics of fishery management is a fascinating subject because of the richness of the problem and the number of possible solutions. The externalities present in fisheries, coupled with the common property nature of the resource, cause divergencies between the market solution and the socially optimum solution. In this framework, the "invisible hand" guarantees that the market will arrive at a solution that is suboptimal.

The economic theory of commercial fisheries that is developed can be called correct, if sympathetically interpreted. However, the preponderant lack of rigor and the lack of correspondence between the most commonly used model and the models in the mainstream of micro-economics indicates there is much room for improvement. This paper was written to examine recent attempts to correct these deficiencies and to suggest an alternative approach.

As is well known, fisheries as they are currently prosecuted combine interesting economic problems in externalities and common property. There are two externalities present in fisheries. The actual degree to which each affects production depends upon the fishery itself. One externality affects the ability of a vessel to land fish out of a stock of fish and the other affects the stock itself. We will call these the static stock externality (SSE) and the dynamic stock externality (DSE), respectively. The common property nature of a fishery prevents these externalities from being internalized into the decision-making process of the firms in the fishery. The prime tasks of economists should be to attempt to (a) integrate the externalities into classic micro-economic theory, (b) develop operational mechanisms to internalize these externalities, and (c) develop means to minimize or eliminate the suboptimizing effects of the nature of a common property resource.

THE ANTECEDENTS

The principal contributors to the theoretical model that we hope to expand upon and clarify were Gordon[1], Scott[2], and Crutchfield and Zellner[3]. Their papers were seminal and in a sense contained all that will be said here. Smith[4] and Bromley[5] recently attempted to improve upon prior work but, because of several poor assumptions, their contributions add little of substance to the understanding of fishery management.

I. THE MODEL

THE BIOLOGICAL AND YIELD FUNCTIONS

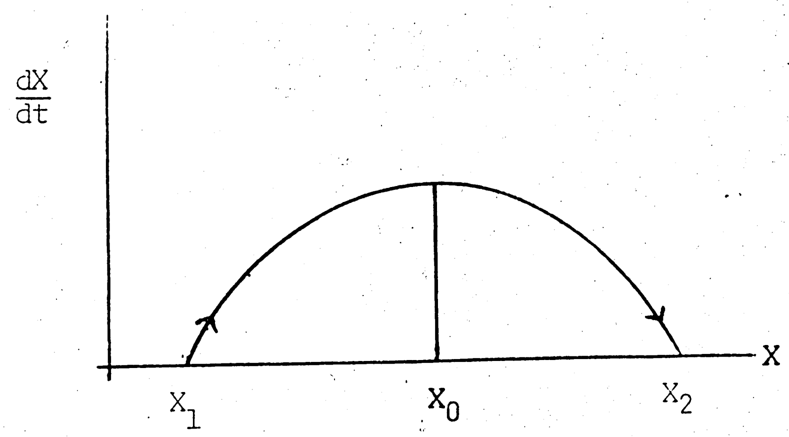
The special nature of economic models of commercial fishing is determined by the interaction of fishermen and a stock of fish. The simplest model of the growth of a fish population is that implied by a logistic model. In such a model the growth of the bio-mass is hypothesized to be a function of the size of the bio-mass and follows the sigmoid law of growth. By this law, a small bio-mass grows slowly, an intermediate size bio-mass grows rapidly, and a larger size bio-mass decreases in the rate of growth as it approaches the maximum size a particular region of the ocean can sustain. This is shown in equation (1).

$$(1) \quad \frac{dX}{dt} = f(X)$$

where X is the size of the bio-mass and dX/dt is the growth of the bio-mass per unit of time. If there is no fishery, a bio-mass will grow to some maximum that depends upon food supplies. areal extent of its habitat, its environment, and its predators.

It is not our purpose here to go into an extensive discussion of the properties of the logistic growth model. This has been adequately handled by others.[6] The hypothesized growth characteristic for a fish population is that shown in figure 1.

Figure 1. Growth as a Function of the Bio-Mass

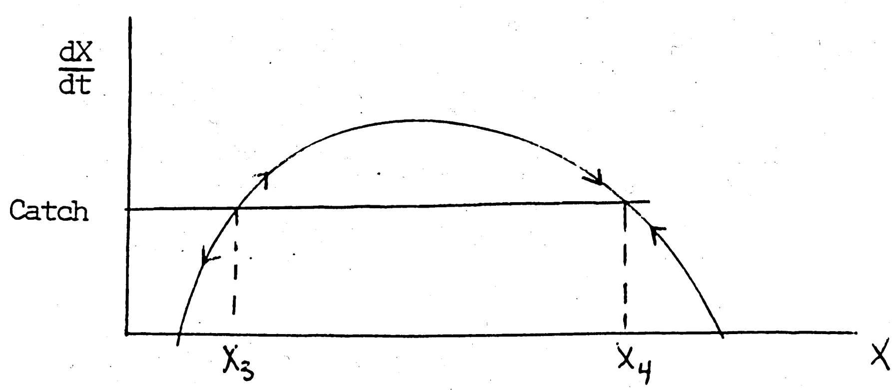


There are 2 values of the population (X) for which the rate of change, dX/dt = 0; however, X_1 is unstable and X_2 is stable. X_0 is the value of X for which dX/dt is a maximum.

The actual relevance of such a model to the study of a particular species is, of course, an empirical question. In some species the variance of year class strengths is so large that it does not appear to be applicable. The model, then, may be more relevant to the behavior of several species at once or even of an entire community. We use the model because of its simplicity and because it gives us a place to begin to understand more complex systems. If a population which is being exploited conforms to such a model it will be in equilibrium whenever the catch is equal to growth of the bio-mass.

When fishermen begin to exploit a fish population, the population will be reduced from its virgin state and, as it is reduced, the growth-rate of the population will increase. If a catch of less than the maximum growth-rate is maintained at one level long enough, growth will equal the catch. This is shown in figure 2. X_3 and X_4 are levels of the population that are in equilibrium with the catch shown but X_3 is an unstable equilibrium.

Figure 2. Bio-mass Equilibrium for Fixed Catch



The modified growth function is:

$$(2) \quad \frac{dX}{dt} = f(X, nL)$$

where n is the number of vessels, L is the landing per vessel and nL is the catch from the fishery.

The points where dX/dt = 0 maps out the sustainable yield function. Of course, we are not interested in the relation between population, growth, and catch per se, but the sustainable yield function provides the basis for the understanding of the dynamics of the fishery. It is the source of the dynamic stock externality (DSE) in a fishery. As will be shown, since X enters into the production function of a firm, an increase in total catch will, after a period of adjustment, decrease X, thereby decreasing a firm's catch.

THE PRODUCTION FUNCTION

To be successful, a fisherman needs much information and must use this information skillfully in making decisions. We will abstract from this and assume that fishing firms are homogeneous, that is each firm consists of a vessel and crew identical to those of all other firms, they all fish the same number of days. Further, we will assume that each firms fishes independent of other firms and that the fish are randomly distributed throughout the fishery.

Given the above assumptions, the catch of a single firm will be a function of the fish population and the fishing power of the standard vessel. The catch of a second firm will be less than that of the first firm because X will have been reduced by the first firm's catch. The marginal catch of additional firms will always be less than the average. In practice, with all firms fishing at the same time, each firm will have the same average catch and the average will decline as new firms enter. Therefore, the firms' output for a given population will be as follows:

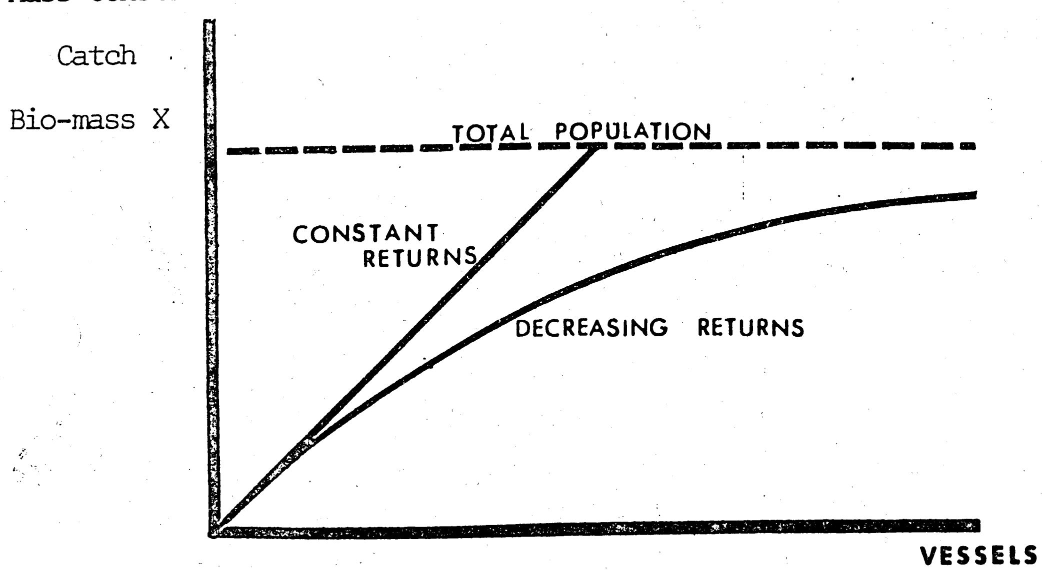
(3) $L = g(n,X)$

under the assumptions we have made, it can be shown that $\frac{\delta L}{\delta n} = g_1 < 0$. The fact that g_1 is negative is the source of the static stock externality (SSE) and means that the entry of additional firms causes a reduction in the average catch of existing firms. This reduction in catch of all other vessels is not taken into account by an entering firm since it will catch the new average and will not be charged for the reduction from the previous average catch per vessel which **was** caused by its entry.

In the development of his model, Schaefer[8] implicitly assumes g_1 is a constant. This can happen only if the bio-mass spontaneously increases its density as the number of vessels increases. We can only assume that he made this assumption because it would ease the task of estimating the yield function. Schaefer's assumption could introduce errors into estimates of maximum sustainable yield in certain fisheries.

The actual importance of the SSE depends upon the fishery. In the Gulf shrimp fishery, where the shrimp are an annual crop and the DSE is not applicable, the SSE is the factor that ultimately limits the vessel's catch. In the halibut fishery, where the annual catch is a small part of the bio-mass and the DSE is operative, the SSE is probably much less important. The ground-fish fishery is where both the DSE and the SSE might be operative. The hypothesized relationship, for a constant population, between the number of vessels and the catch is shown in figure 3, where the catch approaches the population assymtotically as the number of vessels increases.

Figure 3. Total Catch as a Function of Vessels Holding the Bio-Mass Constant



THE COST FUNCTION

The total cost of operating a fishing vessel will be assumed to be equal to its opportunity cost. That is, the total cost is invariant to a vessel's output over a wide range, as shown in equation (4).

(4) $C = n\Phi$

where C is total cost of all the vessels in a fishery and Φ is opportunity cost for a single vessel. This is a standard assumption used by almost all previous writers.[9]

The assumption of constant total cost of operating a vessel should not be confused with average cost and marginal cost of a unit of output. The latter two, of course, will vary with output which depends upon the number of vessels in the fishery. Marginal cost and average cost of output are relationships derived from the cost (**Eq. 4**), growth (Eq. 2), and production (Eq. 3) functions. They can be derived in the following way: First, the growth and production functions are solved for yield in terms of the number of vessels. This gives equation (5).

(5) $nL = h(n)$

We can differentiate this to obtain marginal yield, or:

(6) $\frac{d(nL)}{dn} = h_1$

The average cost (AC) function is then, simply, total cost divided by total yield, or:

(7) $$AC = \frac{n\ \Phi}{h(n)}$$

The marginal cost function (MC) is simply the cost of an extra factor divided by the marginal yield, or:

(8) $$MC = \frac{\Phi}{h_1}$$

THE DEMAND FUNCTION

The demand function we will use is quite straightforward. We will simply assume that the price of the fisheries output is an inverse function of the quantity landed.

(9) $$P = j(nL)$$

The Gordon model is unable to handle even this rather straightforward demand equation. In this model, price must be given as a parameter before it can give a solution as to proper resource allocation. As a result of this deficiency, the model can give only particular solutions to problems rather than a general solution.

THE PROFIT AND ENTRY FUNCTIONS

These functions are discussed under two situations -- without a management system and with a management system.

Without Management

Profits will be generated in a fishery whenever price is greater than average cost. Our profit function is:

(10) $$\Pi = P\text{-}AC = j(nL) - \frac{n\,\Phi}{h(n)}$$

where Π is pure profits to the firm.

Within the terms of the model, i.e., fixed behavior on the part of fishermen, profits will be dissipated as new fishermen enter the fishery. This situation will continue as long as price is greater than average cost, in accord once with usual theory of industry behavior. The rate at which entry takes place will depend upon such factors as: (1) the ease of transferability from other fisheries, (2) the ease of construction of new vessels, (3) the length of time it takes to adequately train new fishermen, and (4) the length of time it takes the knowledge of the existence of profits to become known.

In equation (11a), $\delta 1$ is defined as the rate of entry in a fishery, where the value of $\delta 1$ depends upon the above factors.

(11a) $$\frac{dn}{dt} = \delta_1 \Pi, \text{ when } \Pi > 0$$

When losses are being experienced, vessels will leave the fishery as shown by (11b):

(11b) $$\frac{dn}{dt} = \delta_2 \Pi, \text{ when } \Pi < 0$$

Where δ_2 is the rate of exit from a fishery. There is no necessity in the general case for δ_1 to be equal to δ_2.

Conditions underlying (Eq. 10) assure that misallocation of resources will take place in a fishery because under the terms of the model, decisions are made on the basis of average rather than marginal cost.

Virtually all writers on the economics of fisheries have recognized this principle but, unfortunately, the discussion has been directed toward a discussion of what a sole owner's decisionmaking should entail. This has prevented much of the discussion from becoming directed to the problem of optimal management when there are many firms.

With Management

Resource allocation in fisheries must be handled by an authority capable of making the proper economic decisions. If such an authority were established it should make decisions using a profit function based on marginal cost:

$$(12) \qquad \Pi = P\text{-}MC = j(nL) - \frac{\Phi}{h_1}$$

The entry and exit functions remain as before. The authority would allow vessels to enter a fishery whenever price is greater than marginal cost and would limit entry whenever price is less than marginal cost.

When price is equal to marginal cost, price may be greater than average cost. Therefore, a proper allocation of resources may give the vessels in the fishery returns above opportunity costs. To maintain equity between those included and those excluded, these excess returns should be removed. In a less mechanistic model their removal is an absolute necessity.

MODEL SUMMARY

The model may be summarized as follows:

(13) $\frac{dX}{dt} = f(X,nL)$ Population growth curve

(14) $nL = ng(X,n)$ Total landings

(15) $C = n\,\Phi$ Total cost

(16) $P = j(nL)$ Demand curve

For a fishery with free access the equilibrium conditions will be

(17) $\Pi = j(nL) - \frac{n\,\Phi}{h(n)} = 0$

For a fishery regulated to ensure optimum resource allocation the equilibrium conditions will be

(18) $\Pi = j(nL) - \frac{\Phi}{h_1} = 0$

(19) $\frac{dn}{dt} = \begin{matrix} \delta_1\Pi & \text{when} & \Pi>0 \\ \delta_2\Pi & \text{when} & \Pi<0 \end{matrix}$ Entry Function

There is only one instrumental variable in the system -- the number of firms. If the fishery is not producing at a social optimum, it is the only variable that can be used to correct it.

A second possible instrumental variable, net mesh size, has been suggested by biologists and given extensive treatment in the work of Beverton and Holt[10]. It is theoretically possible to manipulate the size at which fish are first captured by changing the size of the mesh in the fishermen's net. Whether or not this is a practical possibility in anything but limited circumstances is an open question.[11] This could have been added to the model with little extra effort, but our own feeling is that it tends to obfuscate more essential relations.

II AN EXAMPLE

Let us now present an example. All adjustments will be assumed to be instantaneous. First, we have a quadratic growth function:

(20) $$\frac{dX}{dt} = aX - bX^2 - nL$$

The growth function has the properties that growth is a maximum when $X = a/2b$ and growth is zero when $X = 0$ and $X = a/b$.

Second, we have a production function:

(21) $$nL = (1-(1-K)^n)\,X$$

a single vessel and $0 < K > 1$. The production function has the properties that $d(nL)/dn \quad 0$, which means that an additional vessel always increases the total catch, and $d^2(nL)/dn^2 \quad 0$, which means that marginal landings always decline.

The system will be in equilibrium when the growth of the population equals the catch, or:

(22) $$\frac{dX}{dt} = nL, \text{ or}$$

$$aX - bX^2 = (1-(1-k)^n)X$$

We can solve this equation for the population in terms of the number of vessels or

$$(23) \qquad X = \frac{(a-1) + (1-K)n}{b}$$

Differentiating (Eq. 23) with respect to n shows us the bio-mass decreases as the size of the fleet increases or

$$(24) \qquad \frac{dX}{dn} = \frac{(1-K)^n \log (1-K)}{b}$$

The expression is negative because the log of a number less than 1 is negative and b and (1-K) are positive.

Substituting (Eq. 23) back into (Eq. 21) gives the equilibrium catch in terms of the number of vessels.

$$(25) \qquad nL = (1-(1-K)^n)\ ((a-1)+(1-K)^n)/b$$

This expression contains within it the externalities represented by both the resource and the production function.

An interesting result can be obtained in (Eq. 25) if we let n go to infinity. In this case we have

$$(26) \qquad \lim_{n \to 0}(nL) = \frac{a-1}{b}$$

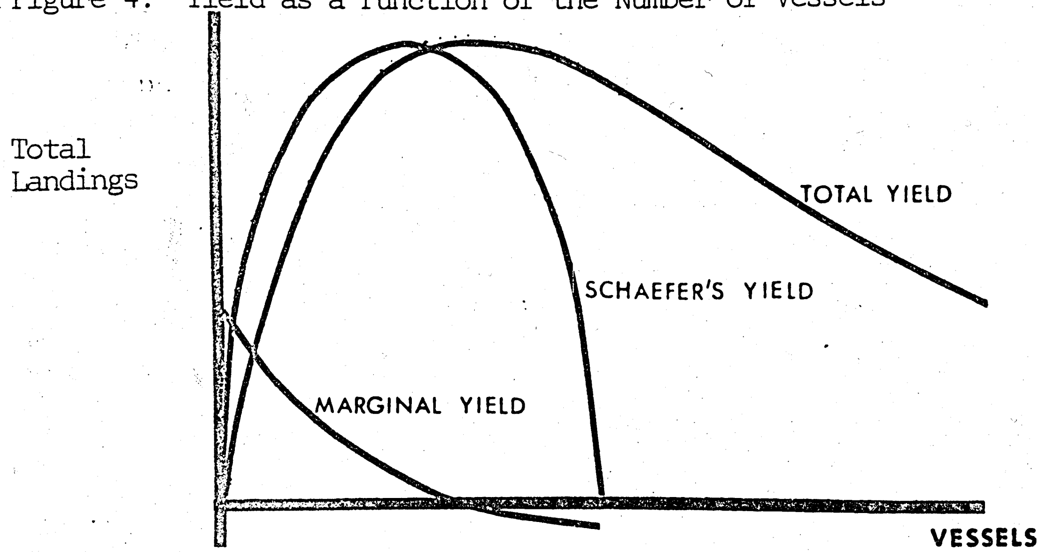
We can interpret this to mean that the total catch will approach (1) some limit that might be zero as the bio-mass is driven to extinction, or (2) the weight of an entire year class as it reached the age of recruitment. The equivalent function derived by Schaefer[12] has no bound and indeed goes to minus infinity as a limit which, of course, has no meaning.

Marginal landings with respect to the entry of vessels are given by the derivative of (25) with respect to n and is:

$$(27) \qquad \frac{d(nL)}{dn} = \frac{(2-A)(1-K)^{n} \log (1-K) - 2(1-K)^{2n} \log (1-K)}{b}$$

The relationship between the number of vessels and catch and marginal catch is shown in figure (4). Yield increases and the decreases approaching its limit assymtotically.

Figure 4: Yield as a Function of the Number of Vessels



As well as the yield curve derived here, another, using Schaefer's yield curve, has been plotted with the same parameters. The yield curve derived here does appear to fit _a priori_ expectations better than Schaefer's.

This is the point at which the biologists' analysis stopped. Long ago, biologists became aware of the social waste involved in letting so many vessels enter a fishery that marginal catch is negative. Economists have been fond of pointing out that fishing up to the point where marginal landings equal zero is an optimum only if opportunity costs are zero at that point.

(28) The total cost function is:

$$C = n\Phi$$

which is, of course, linear. We have assumed that if the fishery expands, factors of production will be avilable to it at constant prices. The marginal cost of factors is the derivative of total cost with respect to n; or

$$(29) \quad \frac{dC}{dn} = \Phi$$

Of course, these relations in themselves are not very stimulating. We are interested in the derived relationship between factor inputs and outputs, in this case between vessels and landings.

Average cost per unit of output is total cost divided by total landings or;

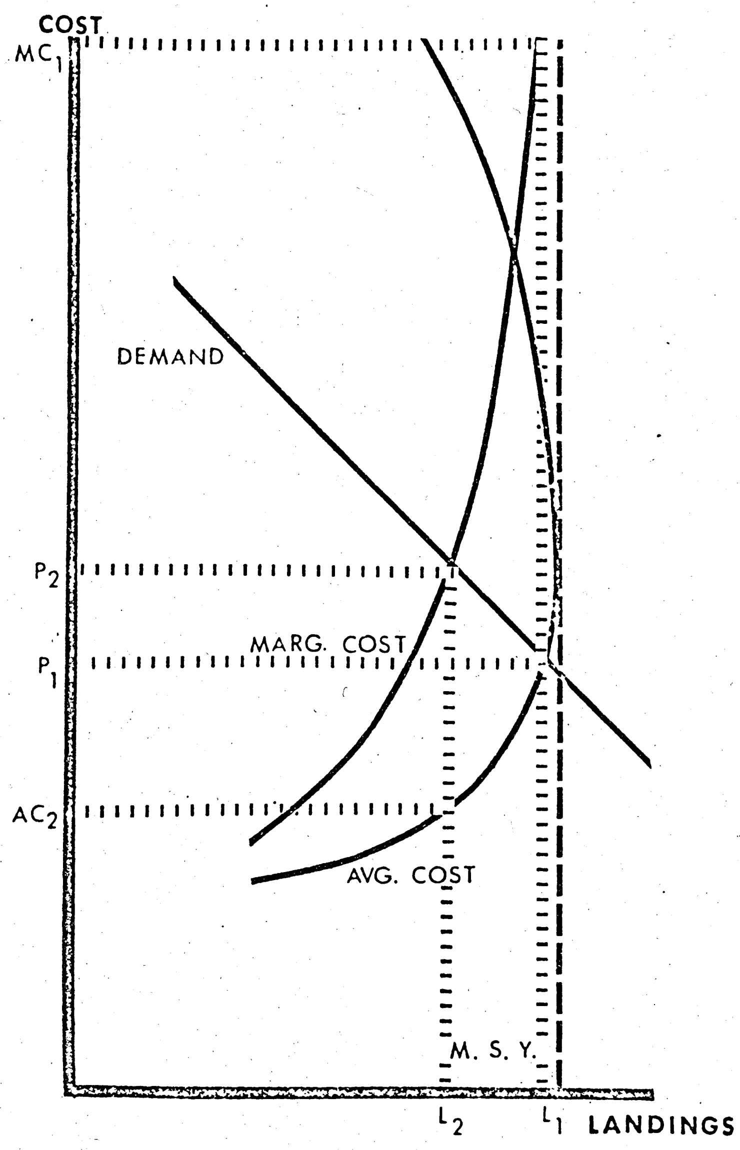
$$(30) \quad AC = \frac{n\,\Phi}{(1-(1-K)^n)((a-1)+(1-K)^n)/b}$$

The marginal cost of output is the marginal cost of factors divided by marginal output:

$$\text{(31)} \quad MC = \frac{\Phi}{((2-a)(1-K)^{n}\log(1-K) - 2(1-K)^{2n}\log(1-K))/b}$$

The average and marginal cost functions are plotted in figure (5). The average cost function is a backward bending supply curve. The marginal cost, under the present assumptions, lies above the average cost function and approaches maximum sustainable yield asymtotically. The marginal cost function is not defined for the backward bending portion of the average cost curve.

Figure 5. Average and Marginal Cost Curves and the Demand Curve



The demand function we will use is a simple linear function where price is an inverse function of the quantity landed. A simple demand curve is plotted on figure (5).

$$P = c - d(nL) \tag{32}$$

As stated previously, the Gordon model cannot handle even this simple demand function, as it is constrained to fixed prices.

THE SOLUTIONS

The solutions to the system are found by equating (Eq. 32) to (Eq. 30) and (Eq. 31) and solving both sets for n. Of course, the resulting equation is too complex to solve directly so we must resort to numerical methods. Having found n, prices and landings can be arrived at simply.

The Market Solution

As shown in figure (5) the market solution to resource allocation in the fishery tends to be suboptimal. The market solution shown is landings of size L_1 which is sold for a price P_1. At L_1, however, the cost of bringing the last unit of output to the market is MC_1 which is in excess of what consumers will be willing to pay for it. This means that resources are not going to their highest valued uses and total output in society is lower than it would be with proper allocation.

The Socially Optimum Solution

Proper resource allocation requires that resources be used only up to the value of that unit of output. If a public authority were managing a fishery for proper economic goals, it would determine the number of vessels that would produce the proper output, in this case, production of L_2, which would be sold for a price of P_2. At L_2, the average cost of the fish, AC_2, is less than price for which it could be sold. This means there will be a quasi-rent accruing in the fishery. Under the assumptions of the model, nothing further would happen. The quasi-rent would be distributed in a manner that would be determined by the relative market power of the buyers and fishermen.

The consequences of the relaxation of the assumption of the mechanistic behavior of fishermen will be discussed in the last section.

III OBJECTIONS TO THE MODEL

The model as presented is, in reality, very little different from that originally proposed by Gordon except for, possibly, a little more elegance. There appears to be very few objections within the economic profession to the conclusions drawn from the model. Schaefer[12] (a biologist) suggested that no restrictions be placed on landings unless the unregulated fishery would attempt to produce more than maximum sustainable yield, thereby catching less in the long run.

He said that society might have goals other than economic efficiency. This, of course, is true and we would have a pretty dismal society if we had no goal other than economic efficiency.

There are many instances in the United States economy where economic efficiency is bypassed to achieve some other goal. We need only note the existence of our farm programs and import quotas to recognize that decisions are not always directed toward economic efficiency. We, as economists, can only make certain that the alternatives be taken into account.

Schaefer made the following points that we will deal **with** in order.[13]

1. Agricultural production of protein will not be sufficient to supply world needs without utilizing marginal land. Therefore, the taking of output from a fishery less than maximum yield (i.e., setting output where marginal cost equals price) is socially unwarranted. If the fishery marginal cost curve is properly constructed it will reflect the cost of diverting resources from the production of protein in alternative forms. Therefore, if fishery production is where price equals average cost society's production of protein will be less than it could have been.

2. There is difficulty in applying the model to international fisheries because of a lack of common economic criteria. The economist's reply is that the fishery should be exploited by the nation with the lowest costs and sold to the nations that will pay the highest prices. This solution may not be realistic within the present international framework but does not mean that the model should not be applied, for to do otherwise diminishes world output from its resources.

3. Restricting entry conflicts with a social goal of providing maximum employment opportunities. This is, of course, true; but we also expect output from those employed. In addition, we have come a long way from the time when any make work opportunity could be looked on as appropriate. Indeed, our current problem has been to reduce the excess demand for labor and capital.

The major problem with the model is that it is deterministic and none of the functions in it can be estimated with any degree of precision, as anyone familiar with econometrics will attest. This does not preclude us from saying that the model is not applicable but rather that there will be a great deal of judgement needed to implement it and make it operate smoothly.

A second problem with the present model is that it does not adequately account for time preferences. Crutchfield and Zellner[14] worked with the problem of time and we hope to integrate this element more fully in subsequent work.

It can be demonstrated in many fisheries that there is some level of fishing that is/or will be excessive. The actual line of demarcation between what is and is not excessive will never be very precise. Our demand and production functions are knowable with even less precision than the biological parameters. The mechanics of managing a fishery within a broad range of uncertainty will be the subject of a later paper.

IV CONCLUSION

The model, as developed, has relied upon strong assumptions about the functions that underlie the exploitation of a fishery. The actual correspondence of these functions to any fishery that exists is at best tenuous. Therefore, we must ask whether this discussion is only a questionable exercise in an economist's fancy.

The biologist's model of the exploitation of a fishery has been an important contribution because it shows the necessity for conserving the fishery resource. Vehement arguments can be raised as to whether the model has been correctly estimated but, in general, the logic of the model has to be correct.

The economist, on the other hand, has a model that is concerned with the conservation of all resources -- the fishery, labor, and capital. Because the economist's model forces administrators to make more difficult choices than the biologists' model which simply limits the total catch, the economists' model has not been implemented. The upshot of this is that there are many fisheries with much redundant capital and labor. The salmon, oyster, and halibut fisheries are prime examples of waste inherent in some of our current fishery management programs.

ACKNOWLEDGEMENTS

The author would like to express his appreciation to Dr. F. V. Waugh for his help in working out some of the more difficult mathematical functions. Thanks also to Dr. A. S. Sokoloski for encouragement, ideas, and help in getting the paper to completion on time.

FOOTNOTES

1. Gordon, H.S. "The Economic Theory of a Common Property Resource: The Fishery" Journal of Political Economy, LXII, No. 2 (April 1954), 124-142.

2. Scott, A. "The Fishery Objectives of Sole Ownership," Journal of Political Economy, LXIII, No. 2 (April 1955), 116-124.

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7. Beverton, R.J.H. and Holt, S.V. On the Dynamics of Exploited Fish Populations ("Fisheries Investigations," Vol. XIX, Sec. 2) London: Ministry of Agriculture, Fisheries and Food, 1957.

Sette, O.E. "Perspective for a Multispecies Fishery," California Marine Research, Vol. 13, Jan. 1969, 81-87.

8. Schaefer, M.B. Op. cit. p. 31.

9. Smith, V.L., op. cit. is the one notable exception. He made very serious errors in his analysis because of his misspecification of the cost function. Comments have been submitted to the journals correcting his error.

10. Beverton and Holt, op. cit.

11. The lobster pot fishery is a case where size manipulation is possible because each captured lobster can be measured and returned

small (or too large). Some biologists believe that the gear in a trawl fishery is so destructive that some species are killed when enmeshed even though they are small enough to escape.

12. Schaefer, M.B. "Some considerations of Population Dynamics and Economics in Relation to the Management of Commercial Marine Fisheries," Journal of the Fisheries Research Board of Canada, XIV, No. 5 (Sept. 1957), p. 673.

13. Schaefer, M.B. ibid, p. 679.

14. Crutchfield, J.A. and Zellner, A. op. cit., p. 112.