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A MODEL FOR DETERMINING OPTIMAL MULTI-NATIONAL EXPLOITATION OF A MARINE FISHERY

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A Model for Determining Optimal Multi-national Exploitation of a Marine Fishery

The marine fishery is an example of a renewable common property resource and as such, exhibits a distinguishing characteristic which results in unusual economic implications. More precisely, ownership of or property rights to the common property resource are not clearly defined. Thus the resource can be exploited by more than one economic agent, and in the case of the marine fishery, by more than one nation. Furthermore, no single vessel owner or nation can prevent another from harvesting a particular fishery resource.

Using the fishery as an example, Gordon (1954) developed an economic theory of common property resource use, and in so doing, defined optimum exploitation of a fishery as that which would occur if in fact the fishery were private property and were being managed by a profit-maximizing sole owner. However, since the fishery is not private property, Gordon viewed the harvesting process as being characterized by uncontrolled competitive exploitation which continues until rent or pure profit is driven to zero and stock depletion occurs. Clearly such a situation does not meet the criterion for optimum exploitation of a fishery.

Gordon's work is based on a static analysis, but determining an optimal marine fishery management program is essentially a problem in intertemporal resource allocation. Thus, its proper solution may require the use of a dynamic optimization technique. One such technique is applied optimal control which has in fact been employed by some authors, notably Quirk and Smith (1969), Brown (1974), and Plourde(1970), in examining the intertemporal aspects of fishery resource management.

Viewed within the above context, the marine fishery management problem becomes one of choosing values for decision or control variables, such as landings or fishing effort, in such a way that a specified objective functional is maximized over a given time horizon. The values of these decision variables, along with a given initial stock of fish and the equation describing the population dynamics of the species, determine the magnitudes of the state variable or fish stock over time.

In recent years, uncontrolled multi-national exploitation of the marine fishery resources in U.S. coastal waters has resulted in stock depletion of many commercially desirable species. Partially in response to this problem, Congress recently passed the Fishery Conservation and Management Act of 1976 which established eight Regional Fishery Management Councils and, as of March 1, 1977, extended jurisdiction of the United States over all fishing activity occurring in coastal waters within 200 nautical miles of shore. This implies, among other things, that no unauthorized fishing by foreign fleets will be allowed within the 200-mile zone. Thus with the advent of the regional councils and extended jurisdiction comes the possibility for development and implementation of programs which efficiently manage the marine fishery.

The purpose of this paper is to outline the development of a general model which may be employed by a central-decision maker (i.e., Regional Fishery Management Council) in managing a single-species marine fishery characterized by multi-national exploitation. The development of such a model involves specifying relevant biotechnical and economic relationships in the most general sense, combining these with the principles of optimal control theory, and deriving solutions which maximize resource rent. Utilizing the continuous-time examples developed by Quirk and Smith (1969), Brown (1974), and Plourde (1970) as a basis, a discrete-time bioeconomic model is constructed and solutions are presented.

I. Specification of Biotechnical and Economic Relationships and Statement of Problem

An essential aspect of the model is the biotechnical functional relationship. The one used here is essentially the discrete-time equivalent of that used by Smith:

$$N_{t+1} = f(N_t) - \sum_{i=1}^{n} Y_{i,t} \qquad t = 0, \ldots, T-1 \tag{1}$$

where N_t and N_{t+1} represent population sizes of the fishery in units of biomass in successive time periods and $Y_{i,t}$ represents total landings from the fishery by country i in time period t. Since, by assumption, more than one nation harvests this fishery, $\sum_{i=1}^{n} Y_{i,t}$ is the sum of landings in time t of all nations engaged in commercial exploitation of the fishery.

The important economic relationships are the inverse demand function, and the industry total revenue and total cost functions. It is assumed that total landings from all nations are sold ex-vessel in a single market, and so price per unit of output from the fishery, P_t, may be expressed as some function of total output:

$$P_t = \phi\left(\sum_{i=1}^{n} Y_{i,t}\right) \qquad t = 0, \ldots, T-1 \tag{2}$$

Thus, industry total revenue in time t, or price per unit of output times total output, can be written as follows:

$$R_t = \left[\phi\left(\sum_{i=1}^{n} Y_{i,t}\right)\right]\left[\sum_{i=1}^{n} Y_{i,t}\right] \qquad t = 0, \ldots, T-1 \tag{3}$$

Finally, in order to express the varying costs faced by each nation, let the industry total cost function, C_t, be the sum of the individual cost functions of each nation:

$$C_t = \sum_{i=1}^{n} c_i\,(Y_{i,t}) \qquad t = 0, \ldots, T-1 \tag{4}$$

The objective of the central decision-maker is to maximize the sum of discounted net revenues over T time periods plus some function of terminal fish stock, $F[N_T]$, subject to a biotechnical constraint. Utilizing (1), (3) and (4) and given $\rho = \frac{1}{1+r}$, where r is a specified rate of discount, the problem is formalized below:

$$\text{MAX NR} = \sum_{t=0}^{T-1} \rho^t \{R_t - C_t\} + F[N_T]$$

subject to:

$$N_{t+1} = f(N_t) - \sum_{i=1}^{n} Y_{i,t} \qquad t=0, \ldots, T-1$$

or, substituting for R_t and C_t:

$$\underset{Y_{1,t}\cdots Y_{n,t};\; N_T}{\text{MAX NR}} = \sum_{t=0}^{T-1} \rho^t \left\{ \left[\phi\left(\sum_{i=1}^{n} Y_{i,t}\right)\right]\left[\sum_{i=1}^{n} Y_{i,t}\right] - \sum_{i=1}^{n} c_i\left(Y_{i,t}\right)\right\} + F[N_T] \tag{5}$$

subject to:

$$N_{t+1} - f(N_t) + \sum_{i=1}^{n} Y_{i,t} = 0 \qquad t = 0, \ldots, T-1$$

$$Y_{i,t} \geq 0 \;\forall\; i = 1, \ldots, n;\; t = 0, \ldots, T-1$$

$$N_t \geq 0 \;\forall\; t = 0, \ldots, T$$

II. The Problem Viewed as an Exercise in Optimal Control

The above problem can be viewed as a discrete-time optimal control problem with N_t representing the state variable, thereby permitting the population dynamics to be described by the following state transition equation:

$$N_{t+1} = h_t\,(Y_{1,t}, \ldots, Y_{n,t};\, N_t) \qquad t = 0, \ldots, T-1 \tag{6}$$

where $Y_{1,t}, \ldots, Y_{n,t}$ are the control variables which, along with N_t, determine the value of N_{t+1}.

The objective functional in (5) can be rewritten in the following general form:

$$\pi = F(N_T) + \sum_{t=0}^{T-1} \rho^t \;\{L_t\,(Y_{1,t}, \ldots, Y_{n,t};\, N_t)\} \tag{7}$$

The problem here, given an initial value for N_0, is to find the values of the control variables $Y^*_{1,t}, \ldots, Y^*_{n,t}$, $t = 0, \ldots, T-1$, and the implied values of the states, N^*_t, $t = 1, \ldots, T$, which maximize the sum of discounted net revenues, π. In order to accomplish this, (6) must be affixed to (7) with multiplier sequence λ_t, in the following manner:

$$\bar{\pi} = F(N_T) + \sum_{t=0}^{T-1} \rho^t \{L_t(Y_{1,t}, \ldots, Y_{n,t}; N_t) + \rho\lambda_{t+1} \left[h_t (Y_{1,t}, \ldots, Y_{n,t}; N_t) - N_{t+1} \right]\} \tag{8}$$

Then the current value Hamiltonian may be defined as:

$$H_t = \rho^t \{L_t (Y_{1,t}, \ldots, Y_{n,t}; N_t) + \rho\lambda_{t+1} \left[h_t (Y_{1,t}, \ldots, Y_{n,t}; N_t) \right] \} \tag{9}$$

so that (8) may be rewritten as follows:

$$\bar{\pi} = F(N_T) + \sum_{t=0}^{T-1} \left[H_t - \rho^{t+1} \lambda_{t+1} N_{t+1} \right] \tag{10}$$

Totally differentiating $\bar{\pi}$ yields:

$$d\bar{\pi} = \left[\frac{\partial F}{\partial N_T} - \rho^T \lambda_T \right] dN_T + \sum_{t=0}^{T-1} \{\left[\frac{\partial H_t}{\partial N_t} - \rho^t \lambda_t \right] dN_t + \frac{\partial H_t}{\partial Y_{1,t}} dY_{1,t} + \ldots + \frac{\partial H_t}{\partial Y_{n,t}} dY_{n,t}\} \tag{11}$$

Thus, first order necessary conditions for maximization of $\bar{\pi}$ require that:

$$\frac{\partial H_t}{\partial N_t} = \rho^t \lambda_t \tag{12}$$

$$\frac{\partial F}{\partial N_T} = \rho^T \lambda_T \tag{13}$$

and

$$\frac{\partial H_t}{\partial Y_{i,t}} = 0 \qquad i = 1, \ldots, n \tag{14}$$

From (9) note that:

$$\frac{\partial H_t}{\partial N_t} = \rho^t \frac{\partial L_t}{\partial N_t} + \rho^{t+1} \lambda_{t+1} \frac{\partial h_t}{\partial N_t} \tag{15}$$

and

$$\frac{\partial H_t}{\partial Y_{i,t}} = \frac{\partial L_t}{\partial Y_{i,t}} + \rho \lambda_{t+1} \frac{\partial h_t}{\partial Y_{i,t}} \tag{16}$$

Equating the right-hand side of (14) and the right-hand side of (16) yields an expression for the set of first-order necessary conditions:

$$\frac{\partial L_t}{\partial Y_{i,t}} + \rho \lambda_{t+1} \frac{\partial h_t}{\partial Y_{i,t}} = 0 \tag{17}$$

Equating the right-hand sides of (12) and (15) gives the following result:

$$\lambda_t = \frac{\partial L}{\partial N_t} + \rho \lambda_{t+1} \frac{\partial h_t}{\partial N_t} \tag{18}$$

The interpretation of (18) is that the value of an incremental (marginal) addition to the fish stock in time t, (λ_t), will equal the marginal contribution of the fish stock to the objective function in time, $\left(\frac{\partial L_t}{\partial N_t}\right)$, plus the discounted value of its incremental contribution to the size of the fish stock in period t+1, $\left(\rho\ \lambda_{t+1} \frac{\partial h_t}{\partial N_t}\right)$.

To find the solution of this problem, that is, the optimal control vector sequences, $Y^*_{1,t}, \ldots, Y^*_{n,t}$, $t = 0, \ldots, T-1$, and the values of the states implied by the optimal controls, N^*_t, $t = 1, \ldots, T$, it is necessary to solve a two point boundary problem described by the following system of T(n+2)-1 equations, from (6), (16), and (18):

I. $N_{t+1} = h_t\ (Y_{1,t}, \ldots, Y_{n,t}; N_t) \qquad t = 0, \ldots, T-1$

II. $\lambda_t = \frac{\partial L}{\partial N_t} + \rho\ \lambda_{t+1} \frac{\partial h_t}{\partial N_t} \qquad t = 1, \ldots, T-1$

III. $\frac{\partial H_t}{\partial Y_{i,t}} = \frac{\partial L_t}{\partial Y_{i,t}} + \rho\ \lambda_{t+1} \frac{\partial h_t}{\partial Y_{i,t}} = 0\ \forall \qquad i = 1, \ldots, n$
$t = 0, \ldots, T-1$

with boundary conditions N_0 (given) and $\rho^T\ \lambda_T = \frac{\partial F}{\partial N_T}$.

III. Alternative Formulation of the Problem:

It is possible to pose another discrete time optimal control problem similar to the one presented above. In this second formulation, however, a production function for total catch or landings is specified, and instead of landings, the control variables are fishing effort. Thus total landings of the i^{th} country in time t, $Y_{i,t}$, may be expressed in the following manner:

$$Y_{i,t} = g_i\ (E_{1,t}, \ldots, E_{n,t};\ N_t) \qquad t = 0, \ldots, T-1 \tag{19}$$

where $E_{1,t}, \ldots, E_{n,t}$ represent the amount of fishing effort (a measure of the capital and labor input) employed in harvesting the species under consideration by nations 1, ..., n. Now let $E_{s,t}$ be a representative effort variable in (19). Within the appropriate range of values of $E_{s,t}$, if s = i, then $\partial Y_{i,t}/\partial E_{s,t} > 0$, which implies that an increase in the fishing effort of the i^{th} nation will, ceteris paribus, result in an increase in the harvest of the i^{th} nation. On the other hand, if $s \neq i$, then $\partial Y_{i,t}/\partial E_{s,t} < 0$. This partial represents the crowding externality which accrues to nation i when other nations are harvesting the same fishing grounds. Finally, $\partial Y_{i,t}/\partial N_t > 0$ represents a positive stock externality.

By substituting (19) into (1) and (3), and by expressing total industry costs in terms of fishing effort, $E_{1,t}, \ldots, E_{n,t}$, an alternative formulation of the problem might be the following:

$$\underset{E_{1,t} \cdots E_{n,t}; N_t}{\text{MAX NR}} = \sum_{t=0}^{T-1} \rho^t \left\{ \left[\phi \left(\sum_{i=1}^{n} g_i \left(E_{1,t}, \ldots, E_{n,t};\ N_t \right) \right) \right] \cdot \right.$$

$$\left. \left[\sum_{i=1}^{n} g_i \left(E_{1,t}, \ldots, E_{n,t};\ N_t \right) \right] - \sum_{i=1}^{n} k_i(E_{i,t}) \right\} + F[N_T] \tag{20}$$

subject to:

$$N_{t+1} - f(N_t) + \sum_{i=1}^{n} g_i\ (E_{1,t}, \ldots, E_{n,t};\ N_t) = 0 \qquad t = 0, \ldots, T-1$$

$$E_{i,t} \geq 0 \ \forall\ i = 1, \ldots, n;\ t = 0, \ldots, T-1$$

$$N_t \geq 0 \ \forall\ t = 0, \ldots, T$$

Instead of total landings, $Y_{1,t}, \ldots, Y_{n,t}$, the decision or control variables are now fishing effort or $E_{1,t}, \ldots, E_{n,t}$, and the problem becomes one of finding the optimal control vector sequence $E^*_{1,t}, \ldots, E^*_{n,t}$, $t = 0, \ldots, T-1$ and the implied values of the states N^*_t, $t = 1, \ldots, T$. The solution to this variation of the original optimization problem may be found by solving the sets of equations I, II, and III with boundary conditions, N_0 (given) and $\rho^T \cdot \lambda_T = \frac{\partial F}{\partial N_T}$, but with the following modifications to I and III as shown in I' and III':

$$\text{I}' \quad N_{t+1} = h_t \ (E_{1,t}, \ldots, E_{n,t}; N_t) \qquad t = 0, \ldots, T-1$$

$$\text{III}' \quad \frac{\partial H_t}{\partial E_{i,t}} = \frac{\partial L_t}{\partial E_{i,t}} + \rho \ \lambda_{t+1} \frac{\partial h_t}{\partial E_{i,t}} = 0 \ \forall \qquad \begin{array}{l} i = 1, \ldots, n \\ t = 0, \ldots, T-1 \end{array}$$

IV. Implications for Future Research

The fishery management model outlined above represents a general framework which may be used for qualitative analyses. As such, it provides a basis for conducting the quantitative analyses required in implementing an actual fishery management program. There are, however, some problems associated with quantifying the marine fishery management model. These are related to both data collection and model construction and solution.

Firstly, there is a dearth of biological data and other information pertaining to the population dynamics of commercially harvested marine species. Other data-related problems inherent in multi-national studies include reconciling measures of catch, fishing effort, and vessel costs as compiled by various countries. Secondly, the existence of interdependencies among the variables of the system may create problems in exactly specifying the biotechnical and economic relationships and in estimating the coefficients of these relationships. Thirdly, the mathematical properties of specific objective and constraint functions might pose problems in deriving optimal numerical solutions.

With the advent of extended jurisdiction and the formation of Regional Fishery Management Councils, the institutional framework now exists for developing and implementing specific fishery management programs. The problems mentioned here suggest areas where future research efforts might be intensified so that effective multi-national marine fishery management and conservation programs can be developed.

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