Bio-Socio-Economic Fishery Models: Labour Dynamics and Multi-Objective Management

Anthony T. Charles

Department of Finance and Management Science, Saint Mary's University, Halifax, N.S. B3H 3C3

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Fishery systems involve complex interactions between resource stocks and the people involved in harvesting those stocks. While the population dynamics of fish stocks have received considerable attention in the ecological literature, the dynamics of human communities dependent on the fishery are equally important. Indeed, the joint dynamics of the fish stocks and the fishermen must be taken into account in determining appropriate management policies. A bio-socio-economic modelling approach is developed here to incorporate these effects within a multi-objective optimization framework. Fishery labour dynamics are determined by the decisions of individual fishermen, with net migration into and out of the fishery (and hence the fishing community) dependent on internal conditions, such as per capita incomes and employment rates, as well as on the state of the external economy. The task of fishery management is then one of balancing multiple objectives – such as conservation, income generation, employment, and community stability – subject to fish and fishermen dynamics. Control theory and simulation methods are used to study the bio-socio-economic dynamics of the fishery system and the interactions of multiple management objectives in determining the resulting fishery equilibrium. Implications for fishery policy development are also discussed.

Tout le système des pêches comporte des interactions complexes entre les stocks de ressources et les personnes qui participent de près ou de loin à leur capture. La dynamique des stocks de poissons a fait l'objet de nombreuses études dans la littérature écologique, mais la dynamique des collectivités humaines qui en dépendent est tout aussi importante. En effet, il faut considérer la dynamique des stocks de poissons et des pêcheurs à la fois afin de déterminer les politiques de gestion appropriées. L'auteur présente ici une approche de modélisation bio-socio-économique afin d'incorporer ces effets dans un cadre d'optimisation à objectifs multiples. La dynamique de la main-d'oeuvre est déterminée par la décision que prend chacun des pêcheurs de pêcher ou de ne pas pêcher, en fonction de conditions internes, par exemple les revenus par habitant et les taux d'emplois, ainsi que de l'état de l'économie externe. L'objet de la gestion de la pêche est donc d'équilibrer les objectifs multiples, notamment la conservation, la production d'un revenu, l'emploi et la stabilité de la collectivité, des objectifs qui sont soumis aux dynamiques des poissons et des pêcheurs. Les méthodes de simulation et théoriques de contrôle servent à étudier la dynamique bio-socio-économique du système de la pêche et les interactions des objectifs multiples de gestion pour déterminer l'équilibre de la pêche. Les implications pour l'élaboration de politiques de pêche sont également traitées.

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For some time now, people have been catching fish. The involvement of people in fisheries has been widely noted both by fisheries scientists (eg. Pringle 1985) and by social scientists (eg. Andersen 1978). Indeed, any fishery management policy is bound to impact on both fish and fishermen. Yet relative to the study of fish population dynamics, considerably less attention has been paid in fishery models to addressing the long-term adjustment dynamics of the fishermen (cf. Smith 1968, Hilborn 1985).

This paper examines the optimal management of fishery systems through the use of "bio-socio-economic" models incorporating fish population dynamics together with the decision-making and adjustment processes of fishing communities and their labour forces. The analysis herein lies broadly in the area of bioeconomic modelling, but differs from that of most such studies in (i) an emphasis on the dynamics of people in the labour force, rather than on fishing vessels or hypothetical "fishing firms," and (ii) the explicit use of multiple objectives for fishery management, to incorporate both societal goals and those of the fishery participants

We shall focus on the situation of a fishery-dependent local economy, operating as one part of a larger multi-sector economy. This is a common occurrence, for example, in Atlantic Canada and in many developing nations. Within this local system, the fishery is sufficiently dominant that its labour force and the overall community population are approximately proportional; as the fishery goes, so goes the community. We shall assume limited labour mobility, with workers able to move into and out of the local economy (i.e. the fishery), depending on both internal and external conditions.

The ideas discussed herein may be particularly relevant in small-scale community-based fisheries, where tradition, family ties, and group decisionmaking are crucial factors. In such situations, employment-sharing, involvement in the "hidden economy," and the behavioral response to income support or unemployment insurance programs may all be relevant. This contrasts, for example, with large-scale "industrial" systems where conventional economic assumptions, based on a "competitive firms" structure, may be reasonable.

Recently, several authors have emphasized the role of fishery labour dynamics in the behaviour of fishery systems and the determination of suitable management policies. A review of the relevant literature may be found in Charles (1988). For example, Smith (1981) examines the relationship between labour mobility and the economic state of fisheries in developing countries, while Panayotou and Panayotou (1986) undertake an empirical study of labour dynamics in the fisheries of Thailand. From a policy perspective, Terkla et al. (1985) argue that "...understanding labour adjustment processes is likely to be crucial for implementing efficient and equitable management policy" throughout the fishing industry. The same authors have studied the "stickiness," or immobility, of fishery labour in the New England fishery (Doeringer et al. 1986).

While most socio-economic fishery research is not based on the use of quantitative models, there are a number of fishery models relevant to our discussion. With respect to optimization analyses, Munro (1976) deals with the optimal dynamics of fish stocks and fish harvests due to adjustments in the opportunity cost of labour, as the employment options of fishermen change over time. Panayotou (1982) provides an equilibrium framework for depicting optimal fishery management subject to various assumptions about appropriate objectives and relevant fishing labour costs. Recently, in a very innovative paper, Krauthamer et al. (1987) incorporate socio-cultural aspects of Texas shrimp fishermen within a dynamic bio-economic simulation model.

A second line of modelling research supplements optimization analyses with behavioral modelling. Perhaps the original theoretical work along these lines is due to Smith (1968), who developed a set of differential equations describing fish population dynamics together with effort dynamics, the latter driven by available profits in the fishery. Recently, the empirical work of Opaluch and Bockstael (1984) examines fishermen's goals other than profit maximization, and the process by which decisions are made concerning such factors as the desired levels of harvesting effort.

The present paper is organized as follows. In the next section, the dynamics of the fish stock and the fishery labour force are discussed. This is followed by the optimization analysis of a fishery system with a general objective function, subject to fish and labour dynamics. The effects on the optimal resource stock and labour force equilibria of specific multiple objectives are examined next, with a discussion of fishery policy applications concluding the paper.

Bio-Socio-Economic Dynamics

The models discussed in this paper focus on two dynamic variables of the bio-socio-economic fishery system; the fish stock itself and the corresponding fishery labour force. Together with the capital stock embodied in the fishing fleet, these variables serve as key inputs to the harvesting process.

With respect to the first of these variables, we shall assume that the fish stock at any time t can be described as a single aggregated population or biomass $x(t)$. Although in most cases a fishery exploits multiple species of fish, each with its own population dynamics, its own age and size structure, and its own degree of variability, such biological complexities will not be considered here, in order to focus attention on interactions between the resource and those utilizing it. The rate of change in the fish stock $x(t)$ is determined jointly by natural reproductive dynamics and harvesting activity:

$$(1) \quad \frac{dx}{dt} = F(x) - h$$

where $F(x)$ is the resource stock's natural growth rate, dependent on the current size of the population $x = x(t)$. The instantaneous rate of harvest $h = h(t)$, representing the quantity harvested per unit time, is to be determined in the fishery management process. The net growth rate, obtained by subtracting the rate of harvest h from the rate of natural growth $F(x)$, is then given by dx/dt.

As pointed out previously, the fishery labour force $L(t)$, and hence the population of the resource-dependent community, can be expected to adjust to changing conditions over time. Within the context of a continuous-time model, we might assume therefore that labour dynamics follow a differential equation of the general form $dL/dt = P(L,x,h,t)$. The exact nature of these dynamics will depend on the specific fishery under consideration, but it seems reasonable to assume that (1) if the fishery appears to be particularly attractive to potential fishermen at a given point in time, the labour force will tend to expand (cf. Smith 1968), and (2) on the other hand, if conditions are poor (for example, if the fish stock $x(t)$ is very small) then the labour force may contract over time.

To allow a more complete exploration of bio-socio-economic interactions within the fishery system, we will make the following specific (albeit arbitrary) assumptions: (3) there is a maximum per capita growth rate ρ for the labour force, reflecting the sum of natural growth and immigration under optimal conditions, and (4) the actual per capita growth rate at any time is given by the product of ρ and a time-dependent multiplier $m(t)$, determined by the relative attractiveness of remaining in the fishery relative to other options in the economy. If $m(t)$ lies close to its upper limit of 1, the per capita growth rate will be close to its maximum ρ, and the labour force will tend to expand. On the other hand, $L(t)$ will decline if $m(t)$ is negative. Finally, in equilibrium, the value of the multiplier will be $m(t) = 0$, implying no growth or decline in the labour force.

With these assumptions, the overall labour force adjustment dynamics are given by:

$$\frac{dL}{dt} = \rho \cdot m(t) \cdot L$$

(Note that this model is meant to deal with the dynamics of an established fishery system. In particular, the possibility of exogenous immigration into a previously uninhabited area cannot occur here, since if $L = 0$ then $dL/dt = 0$. However, with appropriate modifications, the framework presented here should be suitable for analysis of fishery development processes as well.)

Adjustments by fishermen and fishing communities to changing conditions are not likely to occur instantaneously. The set of internal and external conditions existing at any time t determine a target or "natural" level of the labour force, $\bar{L}(t)$, towards which $L(t)$ will adjust gradually. This quantity is analogous to the ecological concept of a population's "carrying capacity." The multiplier $m(t)$ is then determined by the value of the current labour force $L(t)$ relative to the target level $\bar{L}(t)$. A labour force $L(t) < \bar{L}(t)$, being smaller than its "natural" level, will tend to grow ($m(t) > 0$). On the other hand, contraction will occur ($m(t) < 0$) if $L(t) > \bar{L}(t)$.

The logistic model will be used here to capture these assumptions concerning the growth and decline of the labour force. Setting $m(t) = 1 - L(t)/\bar{L}$, we obtain the logistic dynamics:

$$\frac{dL}{dt} = \rho L \left(1 - \frac{L}{\bar{L}}\right).$$

Note however that as conditions change, so too does the "natural" labour force level $\bar{L} = \bar{L}(t)$. Therefore, unlike a simple logistic model, the labour force "carrying capacity" shifts over time, and L(t) adjusts continuously towards a "moving target" determined both by the fishery and by the external economy.

The external factors are summarized in a term $M = M(\cdots)$, representing the maximum labour force under average (or perhaps historical) resource industry conditions, based on current conditions in the nonfishery economy, such as the overall unemployment rate. We will treat the external economy, and hence the term M, as constant, concentrating on changes in the local fishing economy. (In economic terms, a "partial equilibrium" analysis will be carried out.)

The internal conditions in the local economy revolve around the perceived desirability of the fishery to current and potential participants. This is clearly based on many factors, but we shall assume that at any time t, the fishery's desirability can be captured in a function $f(\pi, L, E)$ involving three determinants: (i) fishery rent $\pi(t)$, given by total income minus operating costs and opportunity costs of labour, (ii) the total size of the labour force $L(t)$, measuring the extent of competition for available fishery income as well as serving as a proxy for the overall size of the local population, and (iii) the fishing effort $E(t)$, representing the component of the total labour force which is able to operate in the fishery. (Note that the dimensionless ratio $E(t)/L(t)$ will be used as a form of "employment rate" in the model. If $E(t) = L(t)$, the fishery is operating with full employment of its labour force. If $E(t) < L(t)$, the labour force is underutilized, while $E(t) > L(t)$ represents a situation in which the available work force is over-extended.)

The function f is behavioral in nature, depending on actual fishermen preferences. As an example, assume that fishermen prefer (i) as much opportunity to fish as possible ($E(t)$ close to $L(t)$) and (ii) higher rather than lower incomes. In this case, we obtain a particular form of the function in which f increases with both the employment rate E/L and the per capita income level $(\pi + \tau)/L$, where the constant τ represents net economic transfers entering the fishery system. (Note that in this measure of income, relevant labour opportunity costs have been subtracted from total income.) With this function f, which will be used later in the paper, the partial derivatives have signs given by $f_\pi > 0$, $f_L < 0$ and $f_E > 0$. (Throughout this paper, a subscript will denote the partial derivative with respect to that variable; for example $f_\pi = \partial f/\partial\pi$ and $f_{\pi E} = \partial^2 f/\partial\pi\partial E$.)

The function f is taken to be a scale-independent dimensionless function. In other words, average fishery conditions are represented by a function value $f = 1$, regardless of the size of the fishery system, and the natural level (or carrying capacity) of the labour force at any time is given multiplicatively by $\bar{L}(t) = f(\pi, L, E)\cdot M$. The relevant differential equation describing the dynamics of the labour force $L(t)$ can then be written as:

$$(2) \quad \frac{dL}{dt} = \rho L \left(1 - \frac{L}{f(\pi, L, E)\cdot M}\right).$$

The state variables $x(t)$ and $L(t)$ are determined by differential equations (1) and (2), once the harvest level $h(t)$, the fishing effort level $E(t)$, and the rents function π are specified. We shall assume that fishery management is based on control of the harvest h, and that effort E can be determined in terms of h through inverting the "harvest production function" $h = h(x, E, K)$, which relates the output (fish harvest) to the inputs (fish stock, labour effort and capital). Assuming that the capital input is either constant or determined in terms of the labour effort level $E(t)$, we can relate the required fishing effort to the available fish stock and the desired harvest level:

$$(3) \quad E = e(x, h) .$$

The dynamics of the bio-socio-economic system are broadly determined by equations (1), (2), and (3), once the harvest function $h(\cdot)$ is specified. For convenience, a list of the key variables, parameters, and functions used in the model is given in Table 1.

To provide a specific example of the system dynamics, let us assume for the moment the following functional relationships:

(i) logistic fish stock dynamics $F(x) = rx(1 - x/K)$,
(ii) fishing effort $E = e(x,h) = h/qx$,
(iii) rents function $\pi = ph - cE$,
(iv) target labour force $\bar{L} = A\cdot(E/L)^{1/2}([\pi + \tau]/L)^{1/2}\cdot M$

with the parameters set arbitrarily at $r = 3$, $K = 1$, $q = 1$, $p = 1$, $c = 0.01$, $\rho = 0.25$, $A = 2.12$, $\tau = 2$ and $M = 1$ (although the results are robust to the choice of these values).

We assume that at the outset of the management plan the labour force is relatively large, while the fish stock is significantly depleted. Accordingly, to allow regeneration of the fish stock, it may be reasonable to set the rate of harvest at a relatively low level initially, increasing thereafter. For clarity of presentation throughout this paper, we will express such rates

TABLE 1. Key variables, parameters and functions used in the paper.

Variables	
$x(t)$	Fish stock
$L(t)$	Labour force
$\bar{L}(t)$	Target labour force
$E(t)$	Fishing effort
$h(t)$	Harvest level
$\mu_1(t)$	Shadow value of fish stock
$\mu_2(t)$	Shadow value of labour force
Parameters	
r	Intrinsic growth rate of fish stock
ρ	Intrinsic growth rate of labour force
K	Carrying capacity of fish stock
M	Maximum labour force under historical conditions
τ	Net nonfishery transfers into fishery system
p	Price of fish
c	Unit cost of fishing effort
l	Unit opportunity cost of labour
q	Catchability coefficient
δ	Social discount rate
Functions	
$F(\cdot)$	Fish stock growth function
$\pi(\cdot)$	Rents function
$f(\cdot)$	Fishery "desirability" function
$e(\cdot)$	Inverted harvest production function
$B(\cdot)$	Social benefits function

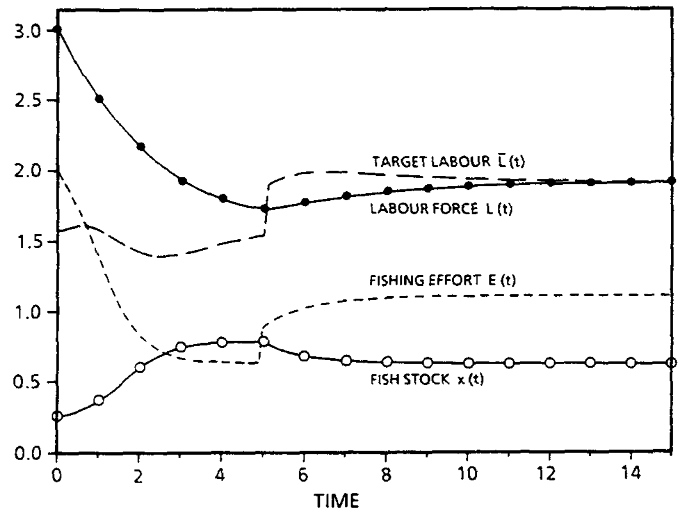

FIG. 1. Fishery system dynamics are shown for the case of an initially small fish stock and a large labour force. Maximum intrinsic growth rates are $r=3$ for the fish population and $\rho=0.25$ for the labour force. The harvest level h, given as a percentage of the fish stock carrying capacity, is assumed to switch from 50% to 70% after the first 5 yr. The labour force $L(t)$ continuously approaches its target level $\bar{L}$, but this quantity varies over time depending on profit rates, effort levels, and the size of the labour force itself.

of harvest h as percentages of the fish stock carrying capacity K harvested per unit time. Specifically in this case, the harvest level is set at 50% of the carrying capacity K per year for the first 5 years and somewhat higher (70%) thereafter. Then Figure 1 depicts the evolution of the resulting fishery system.

While the specifics of Fig. 1 are not important, note that the fish stock, the desired fishing effort, and the labour force all vary over time, with the latter tending continuously towards its constantly shifting "natural" level. In the following sections we turn to the determination of the harvest schedule $h(\cdot)$, using dynamic optimization procedures.

A Bio-Socio-Economic Optimization Model

Before turning to a discussion of multiple objectives in fishery systems, we first consider a general optimization model combining the fish and fishermen dynamics described above with an "objective function" to be maximized in the process of fishery management. This function will then be used as a general framework to incorporate conflicting management objectives.

Assume that the net social benefits obtained at any time t through the operation of the fishery within the local economy are given by a function $B(x,L,E,h)$, determined by the size of the resource stock $x(t)$, the labour force $L(t)$, the actual labour effort $E(t)$, and the rate of harvest $h(t)$. The function B will be treated as a general welfare function in this section, although the fishery rents function $\pi(t) = \pi(x,L,E,h)$ represents a special case. (Note that effort $E(t)$ appears separately in B, but using equation (3), we can substitute $e(x,h)$ in place of E where convenient.)

The social benefits function B can be compared with the "desirability function" f, which deals with the attractiveness of the fishery to fishermen. While there are likely to be some factors (such as per capita incomes) influencing both of these functions simultaneously, there is no reason to assume that what makes the fishery desirable to fishermen in the short term necessarily corresponds to overall socio-economic benefits. Hence we shall treat $f(\cdot)$ and $B(\cdot)$ separately in the analysis, although keeping in mind the potential connections between them.

The fishery optimization problem can be described as that of choosing a harvest function $h(\cdot)$ in order to maximize the sum of benefits $B(x,L,E,h)$ obtained over time, with future benefits suitably discounted relative to the present. This objective can be represented by the following present value maximization:

$$\text{(4)}\quad \underset{\{h\}}{\text{Max}} \int_0^\infty e^{-\delta t} B(x,L,E,h)\, dt$$

where δ is the social discount rate, assumed constant over time.

The dynamic analysis of this model then proceeds by creating the (current-value) Hamiltonian, as follows:

$$\text{(5)}\quad \mathcal{H} = B(x,L,E,h) + \mu_1[F(x)-h] + \mu_2\rho L\left(1 - \frac{L}{f(\pi,L,E)\cdot M}\right)$$

where μ_1 and μ_2, the shadow prices of the fish stock and the labour force, are multiplied by the time derivatives of x and L, respectively. This Hamiltonian represents the total increment to the value of the fishery at any point in time, including immediate benefits obtained (B) and measures of the future value of both fish stock and labour force growth. According to the Pontryagin Maximum Principle (eg. Kamien and Schwartz 1981), the optimal dynamics of these shadow prices are then given by:

$$\text{(6)}\quad \frac{d\mu_1}{dt} = \delta\mu_1 - \partial\mathcal{H}/\partial x = \delta\mu_1 - B_x - B_E e_X - \mu_1 F'(x) - \mu_2\rho L\left(\frac{L}{f^2 M}\right)\cdot(f_E\cdot e_x + f_\pi\cdot\pi_x + f_\pi\cdot\pi_E\cdot e_x)$$

$$\text{(7)}\quad \frac{d\mu_2}{dt} = \delta\mu_2 - \partial\mathcal{H}/\partial L = \delta\mu_2 - B_L - \mu_2\rho\left(1 - \frac{2L}{fM}\right) - \mu_2\rho L^2\left(\frac{(f_L + f_\pi\cdot\pi_L)}{f^2 M}\right)$$

where the partial derivative e_x is determined using the inverted harvest production function of equation (3), while f_π, f_L, and f_E are the partial derivatives of the labour response function, representing the marginal response of the labour force carrying capacity to changes in the economic rent level, the labour force, and the current fishing effort level. The Maximum Principle states that, at any time, the optimal value for the control variable, in this case the harvest level $h(t)$, is either an extreme value (i.e. $h=0$) or is given by setting the partial derivative of the Hamiltonian with respect to the control equal to zero:

$$\text{(8)}\quad \partial\mathcal{H}/\partial h = B_h + B_E e_h - \mu_1 + \mu_2\cdot(\rho L^2/M)\left(\frac{f_E e_h + f_\pi \pi_h + f_\pi \pi_E e^h}{f^2}\right) = 0.$$

Differential equations (1), (2), (6), and (7), together with equation (8), the initial values for x and L, and conditions on μ_1 and μ_2 arising from the Maximum Principle, completely describe the dynamic evolution of the optimally managed fishery system. The first four of these equations give the dynamics of the state variables and the shadow prices, while equation (8) provides the optimal harvest path over time, as a function of x, L, μ_1, and μ_2.

Later in the paper, a simulation approach will be used to examine the optimal bio-socio-economic dynamics. At this point, however, we will focus on the long-run equilibrium behaviour of the fishery system. Setting to zero the rates of change in (1), (2), (6), and (7), and assuming that $h \neq 0$, we obtain the following set of five equations in the five variables x, L, μ_1, μ_2, and h:

$$(9) \quad h = F(x)$$

$$(10) \quad L = f(\pi,L,E)\cdot M$$

$$(11) \quad [\delta - F'(x)]\cdot\mu_1 - \left[\left(\frac{\rho L^2}{f^2 M}\right)\cdot(f_E e_x + f_\pi \pi_x + f_\pi \pi_E e_x)\right]\cdot\mu_2 = B_x + B_E e_x$$

$$(12) \quad [\delta\text{-}\rho(1\text{-}2L/fM)\ \text{-}(\rho L^2/f^2M)\cdot(f_L + f_\pi\cdot\pi_L)]\cdot\mu_2 = B_L$$

$$(13) \quad \mu_1 = B_h + B_E e_h + \left[\left(\frac{\rho L^2}{f^2 M}\right)(f_E e_h)\right]\cdot\mu_2 + \left[\left(\frac{\rho L^2}{f^2 M}\right) f_\pi(\pi_h + \pi_E e_h)\right]\cdot\mu_2$$

where we have $E = e(x,h)$, $B = B(x,L,E,h)$ and $\pi = \pi(x,L,E,h)$, while f and its derivatives are evaluated at (π,L,E). Hence equations (9)–(13) constitute five equations which in theory can be solved for the five equilibrium values of the variables.

Equation (13) can be readily interpreted as a statement that in the optimal equilibrium, one must have "marginal benefits = marginal costs." The left hand side (μ_1) represents the future benefits obtainable from a fish (or unit biomass) left in the sea — this is equivalent to the marginal opportunity cost of an extra unit harvest taken now. The first two terms on the right hand side are the immediate marginal benefits of that extra unit harvest. The third and fourth terms on the right hand side represent future labour benefits induced by the incremental harvest, resulting from (i) the required additional fishing effort, and (ii) the corresponding increase in rents, respectively. (For example, the term $(\rho L^2/f^2M)\cdot f_\pi\cdot(\pi_h + \pi_E e_h)$ is the rents-linked effect of an additional harvest on labour force growth; when multiplied by the shadow value of labour μ_2, this gives the rents-based labour benefits of the marginal harvest.)

The above expressions can be manipulated to obtain insights into the effects of bio-socio-economic dynamics on optimal fishery management. Using equations (12) and (13), the shadow prices μ_1 and μ_2 can be eliminated from equation (11), which can then be re-written:

$$(14) \quad F'(x) + \left[\frac{B_x + B_E e_x + T\cdot M\cdot[f_E e_x + f_\pi(\pi_x + \pi_E e_x)]\cdot B_L}{B_h + B_E e_h + T\cdot M\cdot[f_E e_h + f_\pi(\pi_h + \pi_E e_h)]\cdot B_L}\right] = \delta$$

where the term T is given through equation (10) by:

$$T = \rho/[\delta + \rho - \rho M(f_L + f_\pi\cdot\pi_L)].$$

Since in equilibrium, we have $h = F(x)$ and $E = e(x,h)$ from equations (9) and (3), both equation (14) and the labour equilibrium (10) involve optimal values of just two variables, the fish stock x and the labour force L. Together, equations (10) and (14) therefore constitute simultaneous equations for the two unknowns.

Equation (14) is a "marginal" expression, producing the optimal fish stock size (and hence the optimal harvest) as a balance between the benefits of immediate harvesting and the "opportunity costs" due to foregone future harvests. Indeed, it indicates precisely how the social benefits (B), the rents (π), fishing effort (e), labour dynamics (f), and fish population dynamics (F) interact to determine optimal management.

Equation (14) has the form of a "Modified Golden Rule" (MGR) equation; such expressions, drawn from the economics of capital accumulation, have become common in the theory of resource management (Clark 1976). In its simplest form, without economic factors and with fishery benefits equal to the harvest level ($B = h$), the MGR states that optimal sustainable yield is obtained by equating two rates of change — the marginal rate of fish stock growth, $F'(x)$, and the rate at which society discounts future benefits, δ. In other words, the fish stock is set so that $F'(x) = \delta$.

When benefits $B(x,h)$ are expressed more generally in terms of the harvest and the fish stock size (but without incorporating labour dynamics), Clark (1976) shows that the optimal resource stock x is given implicitly by:

$$(15) \quad F'(x) + \left[\frac{B_x}{B_h}\right] = \delta$$

The solution of equation (15) represents an optimal equilibrium stock size and harvest level, balancing the growth rate of the fish stock (F'), the social discount rate (δ), and the "marginal stock effect," represented by the bracketed term in equation (15). This latter term represents the incremental effects of stock size changes on the benefits function (Clark and Munro 1975). The interpretation is similar, although more complex, for the bracketed term in equation (14).

Equation (15) is clearly a special case of equation (14); the latter simplifies to the basic bioeconomic result in the former if:

(i) changes in the fishery labour force are considered irrelevant to society, with benefits $B(x,L,E,h)$ independent of L ($B_L = 0$),

(ii) the labour force is constant over time, with no dynamic forces in play ($\rho = 0$), or

(iii) the labour dynamics are independent of other variables (x,h,E,π), with the function f constant in equation (2).

In such a case, labour dynamics cannot be controlled within the system, and hence such dynamics do not enter into the calculations of the optimal equilibrium (although they may affect the approach to equilibrium).

Thus equation (15) and its solution represent benchmarks against which the influence of the labour force on social benefits and of labour dynamics on the fishery system can be examined. Indeed, it is possible to examine quantitatively the effects of introducing the labour force into the benefits function $B(x,L,E,h)$. Assume that the extent of this presence is measured by a parameter θ, with $B_L \equiv$ if $\theta = 0$, and with the second partial derivatives $B_{x\theta}$, $B_{h\theta}$ and $B_{E\theta}$ all equal to zero. Then taking a total derivative of both sides of equation (14) with respect to the parameter θ, we can show that:

$$(16) \quad \left.\frac{dx}{d\theta}\right|_{\theta=0} = \frac{[\phi_1\psi_2 - \phi_2\psi_1]\cdot B_{L\theta}}{\phi_2^2\cdot F'' + \phi_2\cdot(B_x' + B_E' e_x + B_E e_x') - \phi_1(B_h' + B_E' e_h + B_E e_h')}$$

where the ϕ_i and ψ_i are given by $\phi_1 = B_x + B_E e_x$, $\phi_2 = B_h + B_E e_h$, $\psi_1 = T\cdot M\cdot[f_E e_x + f_\pi(\pi_x + \pi_E e_x)]$ and $\psi_2 = T\cdot M\cdot[f_E e_h + f_\pi(\pi_h + \pi_E e_h)]$.

If the reproduction function F is concave ($F''<0$) and the benefits B behave normally with respect to x and h ($dB/dx>0$, $dB/dh>0$, $d^2B/dx^2<0$, $d^2B/dxdh>0$) then the denominator in equation (16) is negative. In this case, introducing labour into the fishery benefits function will decrease the equilibrium fish stock size if benefits B increase with L, and the term $[\phi_1\psi_2 - \phi_2\psi_1]$ is positive. This situation will be explored in detail in the following section.

To provide useful interpretations of equations (14)–(16), henceforth specific forms will be adopted for the inverted production function $e(x,h)$, the profit function $\pi(x,L,E,h)$, and the response function $f(\pi,L,E)$ in the labour force dynamics:

(i) Treating capital inputs as either constant or proportional to labour effort, the harvest level h will be assumed proportional to the fish stock x and to a power of the fishing effort E. This Cobb–Douglas production function can be written as $h=qE^a x$ where q is referred to as the catchability coefficient. Hence effort E can be deduced in terms of x and h:

$$(17) \quad E = e(x,h) = (h/qx)^{1/a}$$

(ii) The economic rents function π can be written explicitly as the difference between fishing revenues and costs, the latter being the sum of the variable costs of supplying fishing effort and the opportunity costs of labour in the fishery. Assuming linear costs, with c and l representing the unit costs of effort and labour respectively, and assuming a constant price p per unit harvest, the rents function is:

$$(18) \quad \pi = \pi(x,L,E,h) = ph - cE - lL$$

where equation (17) can be used to express E as a function of x and h. (Note that capital costs are not incorporated here; see Charles (1983) for analyses of fishery models involving joint harvesting and investment decisions.)

(iii) As discussed earlier, the desirability of the fishery may be assumed to depend both on the relative level of participation in the fishery, $E(t)/L(t)$, and on the per capita fishermen income $[\pi(t)+\tau]/L(t)$. Here we shall adopt that specification, with the target labour force $L(t)$ following a log-linear form:

$$(19) \quad \bar{L}(t) = f(\pi,L,E)\cdot M = A\cdot(E/L)^{\alpha}\cdot([\pi+\tau]/L)^{\beta}\cdot M$$

in which exponents α and β lie between 0 and 1. While the net nonfishery transfers τ will be incorporated in simulation results later in the paper, we set $\tau=0$ for convenience in the analytic results presented below.

Using these specific forms, their partial derivatives, and the equilibrium expression $L=f\cdot M$ from equation (10), the Modified Golden Rule equation for any benefits function $B(x,L,E,h)$ can be written:

$$(20) \quad F'(x) + \left[\frac{B_x-(E/ax)\cdot B_E+T\cdot(L/ax\pi)\cdot B_L\cdot\{-\alpha\pi+\beta cE\}}{B_h+(E/ah)\cdot B_E+T\cdot(L/ah\pi)\cdot B_L\cdot\{\alpha\pi+\beta(aph-cE)\}}\right] = \delta$$

where $T=\rho/[\delta+(1+\alpha+\beta)\rho+\beta\rho lL/\pi]$, and the quantities E, π, and f are specified in equations (17)–(19) respectively. Equation (20), and the corresponding version of equation (16), will be examined in detail in the following section, using a benefits function based on specific fishery objectives.

Multiple Objectives and Optimal Fishery Management

Real-world fisheries are managed on the basis of multiple conflicting objectives. Evidence from the fisheries literature (Charles 1988; FAO 1983; Lawson 1984; Regier and Grima 1985) and from actual fishery management suggests the most common declared or de facto fishery goals are (i) resource conservation, (ii) food production, (iii) generation of economic wealth, (iv) generation of reasonable incomes for fishermen, (v) maintaining employment for fishermen, and (vi) maintaining the well-being and viability of fishing communities. In addition, a multitude of other objectives may exist; for example, the generation of foreign exchange through fish exports is often of importance, particularly in developing countries.

While it is widely agreed that multiobjective management is desirable in fishery systems, substantial difficulties are encountered in quantifying the various goals and in providing a framework for comparison between objectives. For example, see Bishop et al. (1981); Healey (1984); Hilborn and Walters (1977); and Keeney (1977) for analysis and discussion of related aspects of these problems.

In this paper, we focus on the set of specifically socio-economic objectives (iii)–(vi) above, incorporating resource conservation and food production implicitly. While most fishery participants would place resource conservation as the top priority in fishery management, this will be treated as a "given" here, with the avoidance of stock extinction incorporated into all management options. Similarly, the objective of food production (harvest maximization), while crucial in developing countries, is not dealt with explicitly but appears instead as part of the "wealth" generated in the fishery — this will be discussed further below.

Among the socio-economic objectives to be considered here, "bio-economic" fishery models have tended to focus primarily on the generation of economic wealth, usually quantified in monetary terms as the "economic surplus" between fishery revenues and fishery costs. We have referred to this above as the economic rent (π), although fishery economists are well aware that "rent" can include much more than strictly monetary, commercial benefits (Christy and Scott 1965).

The measurement of total economic rents will be broadened somewhat here to include not only the rents accruing directly from the fishery, as modelled above, but also rents arising from the "social overhead capital" and infrastructure that has been developed in the fishing communities. This second category of benefits is generated through economic interactions within the community, and hence such rents are assumed to accrue at a level dependent on the size of the relevant population. In particular, they are modelled here as a function $G(L-L^*)$ of the difference between current and historic labour force levels, where the labour force serves as a proxy for the population.

Total rents at any point in time are then given by the sum $\pi(t) + \lambda\cdot G(L(t)-L^*)$, where λ represents the fraction of rents from community infrastructure that are included in our objective function. The first fishery management objective thus involves maximizing the sum of these economic rents, discounted over time.

The average fisherman income, measured by net benefits per capita, is also relevant since this provides a measure of an individual's economic well-being. Specifically, to incorporate equity considerations, we focus on per capita income relative to the average income in the overall economy ($\bar{Y}$), using the term $[\pi(t)/L(t) - \bar{Y}]$. Here, π/L actually represents per capita income net of labour opportunity costs, although this distinction will not be made in the following discussion. In general, $\bar{Y}$ may depend on such external factors as changing unemployment rates, but it will be treated as a constant here.

The third objective, employment, is a traditional concern of fishery managers, particularly in small-scale or isolated fisheries, as are found for example in much of Newfoundland, in native communities on Canada's Pacific coast, and in many parts of the developing world. In such situations, total employment comprises fishermen in the harvesting sector together with those involved in secondary industry (such as fish processing).

Although the effort level $E(t)$ is often used as a measure of actual fishery employment, in this case the employment rate $E(t)/L(t)$ seems to be a more crucial element from the social perspective of a fishing community. Specifically E/L represents the fraction of the labour force that is involved in providing fishing effort at any point in time — if society desires as great a utilization of the labour force as possible, maximizing this objective is appropriate. (Note that a desire for higher fishing effort per se can be captured by decreasing the opportunity cost of effort in the rents function π.)

If in fact the relevant goal is to equalize employment rates across the economy, then a more appropriate objective may involve minimizing the squared difference between the fishery employment rate and that pertaining in the external economy, given by the term $[E(t)/L(t) - \bar{r}]^2$. This then represents a measure of employment "equity." While we shall not consider this case here, it is easily incorporated into the present multi-objective framework.

The fourth objective, fishing community viability (or "health"), is an important factor in any determination of social welfare, yet its appropriate measurement is by no means clear. We assume here that community well-being is not strictly determined by total fishery profit levels or even fishermen income levels, but is better measured using the growth rate of the relevant local population. It is common to view a declining population in resource-based communities as socially detrimental, unless this is due to improving opportunities in the external economy. Conversely, an increasing population tends to reflect a healthy community, assuming constant external conditions. Hence the fourth objective is represented by the derivative of the fishery labour force with respect to time, dL/dt; other things being equal, a growing population is preferred to a shrinking one.

Note that an increasing population clearly may lead to greater unemployment and to declining income levels, but these detrimental effects are included explicitly under our second and third objectives above. The determination of an "optimal" management policy will involve the balancing of these conflicting objectives.

In order to combine these four goals in a multicriteria welfare function in a manner amenable to analysis, we assume:

(i) the social welfare function $B(x,L,E,h)$ is given by a weighted sum of utilities, one for each of the four objectives,

(ii) linear utility functions are appropriate to describe social attitudes towards each objective (thus avoiding the practical difficulties in obtaining and analysing nonlinear utilities),

(iii) the weight a_i placed on objective i is given by the quotient of a dimensionless coefficient w_i, representing the relative importance of that objective, and an average historic value of the quantity measured in that objective. As will be seen below, this makes the analysis scale-independent, since dividing the current value of each objective by its historic value produces dimensionless objectives which do not depend on the actual extent of the fishery system under study. Note that the coefficients $\{w_i\}$ fully capture societal judgements about fishery priorities; their choice is crucial since they determine the relative importance placed on unit changes in each of the objectives.

With these assumptions, and using E/L as the employment objective for now, our overall objective becomes:

$$(21)\quad \underset{\{h\}}{\text{Max}} \int_0^\infty e^{-\delta t}\left\{a_1[\pi + \lambda G(L-L^*)] + a_2\left(\frac{\pi}{L} - \bar{Y}\right) + a_3\left(\frac{E}{L}\right) + a_4\left(\frac{dL}{dt}\right)\right\}dt$$

where all variables and parameters are as in the previous section. The fish and labour dynamics are assumed driven by equations (1) and (2). The economic rents $\pi = \pi\,(x(t), L(t), E(t), h(t))$ are again assumed to depend on the fish stock $x(t)$, the labour force $L(t)$, the harvest $h(t)$ and the fishing effort $E(t)$. The management objective is to choose a harvest policy $\{h\}$ to maximize this multiobjective function.

Equation (21) can be simplified in two regards. First, the average income level $\bar{Y}$ can be dropped from the analysis, since it is independent of the decision variables in expression (21). Second, using integration by parts on the fourth term in equation (21), and noting that $L(0)$ is a constant, the derivative dL/dt can be replaced with δL in the integrand of equation (21). Hence our overall objective function can be rewritten as follows:

$$(22)\quad \underset{\{h\}}{\text{Max}} \int_0^\infty e^{-\delta t}\{a_1[\pi + \lambda G(L-L^*)] + a_2(\pi/L) + a_3(E/L) + a_4(\delta L)\}\,dt.$$

Note that, after performing the present value integrations, the four objectives in equation (22) are measured in very different units: money, money/unit labour, time, and labour. As discussed above, the terms $\{a_i\}$ represent dimensionless coefficients $\{w_i\}$ divided by the historic values of the objectives, given by $[\pi^* + \lambda G(0)]$, π^*/L^*, E^*/L^* and δL^*, respectively. In this way, the objective function is itself dimensionless, and the coefficients $\{w_i\}$ are independent of the size of the fishery system.

The expression in braces in equation (22) can be considered as a welfare function $B(x,L,E,h)$, precisely analogous to that analysed in the previous section. Hence the results of equation (14) carry over to the present model, with suitable partial derivatives B_x, B_L, B_E, and B_h obtained from expression (22). For the sake of clarity, we will also make the following simplifying assumptions:

(i) effort enters linearly in equation (17), so $E = h/qx$ and $a = 1$,

(ii) opportunity costs of labour are omitted from calculations of fishery rents, so that $l = 0$ in equation (18), and

(iii) in equation (19), $\alpha + \beta = 1$, so that the response function f is inversely proportional to labour L.

Then the MGR equation (20) for the optimal fish stock x and labour force L becomes:

$$(23)\quad F'(x) + \left(\frac{h}{x}\right) \times \left[\frac{(a_1 + a_2/L)cE - a_3(E/L) + T\cdot L\cdot B_L\cdot(-\alpha ph + cE)/\pi}{(a_1 + a_2/L)\cdot\pi + a_3(E/L) + T\cdot L\cdot B_L}\right] = \delta$$

where now $T = \rho/(\delta + 2\rho)$ and B_L is given by:

$$B_L = a_1\lambda G'(L-L^*) - (a_2\pi + a_3E)/L^2 + a_4\delta.$$

Again, this equation is solved simultaneously with the labour force equilibrium equation (10) to produce the optimal equilibrium fishery configuration.

Let us now focus on the rent generation and community growth objectives, ignoring per capita income and employment considerations ($a_2 = a_3 = 0$) for now. In addition, we set $a_1 = 1$, without loss of generality, and write the benefits function as:

$$(24)\quad B(x,L,E,h) = [\pi + \lambda G(L-L^*)] + a_4(\delta L) = \pi + \theta g(L)$$

where θ measures the deviation of B from a simple rents function, $g(L) = (\lambda/\theta)\cdot G(L - L^*) + (a_4/\theta)\cdot\delta L$, and the terms (λ/θ), (a_4/θ) are considered constants. Then the MGR expression can be written:

$$(25)\quad F'(x) + \left[\frac{cF(x)/qx - TL\theta g'(L)\cdot[(\alpha pqx - c)/(pqx - c)]}{(pqx-c)/q + TL\theta g'(L)\cdot[x/F(x)]}\right] = \delta.$$

With this model, the effect of allowing for labour benefits in the objective function is captured by the specific version of equation (16), namely:

$$(26)\quad \left.\frac{dx}{d\theta}\right|_{\theta=0} = \frac{[(1-\beta)\,pTL/x]\cdot g'(L)}{(p-c/qx)^2F'' - (c/qx^2)(p-c/qx)(F/x - F') - pcF/qx^3}$$

With F a concave function of the stock size x, we have $F''<0$ and $F/x>F'$. Hence, since the fish stock must satisfy $x>c/pq$ for the fishery to be profitable, the denominator in equation (30) will be negative, and we have:

$$(27)\quad \left.\frac{dt}{d\theta}\right|_{\theta=0} \begin{matrix} > \\ < \end{matrix} 0 \text{ if } g'(L) \begin{matrix} < \\ > \end{matrix} 0.$$

The introduction of the labour force into the objective function influences the optimal resource stock in a manner which depends on whether a larger labour force has a net positive or negative impact on overall benefits. A smaller equilibrium fish stock is desired $[dx/d\theta<0]$ if an increasing labour component increases overall benefits [i.e. $g'(L)>0$], and conversely. For example, if the size of the labour force influences rents from social capital, with $G'(L-L^*)>0$, then the equilibrium fish stock size is reduced, relative to fishery management practices which neglect such labour factors.

This result is somewhat less intuitive than it might at first appear. It is true that higher benefits from current harvesting lead to a lower equilibrium fish stock. Thus if the labour benefits introduced into the objective function were only short term in nature, this would naturally tend to bias the results towards higher immediate exploitation rates and hence a lower long-term stock size (as we see here). However, in fact labour benefits (like rents) represent a flow over time, so that there is no a priori reason that their introduction should affect the balance between short- and long-term management.

Further complicating this is the indirect nature of the interaction between labour benefits and the fish stock dynamics. The introduction of labour benefits makes it desirable to maintain a larger labour force than would otherwise be the case, but given the labour dynamics of equation (2), this can only be accomplished through higher effort levels. This in turn impacts on the resource dynamics, ultimately producing a reduced fish stock size. Overall then, the effects of labour on optimal fishery management can be quite complex. The result in equation (27) need not apply in all cases – we return to this point later in the paper.

TABLE 2. Management objectives, input parameters, and resulting optimal harvest levels (given as percentages of the fish stock carrying capacity harvested per year) are shown for two bio-socio-economic fishery systems with dynamics as in Figs. 2 and 3, respectively. Other model parameters are described in the text.

	System No. 1	System No. 2
Management objectives		
Maximize:	Economic rents	Economic rents + community welfare
Intrinsic growth rates		
Fish Stock	3.00	1.50
Labour force	1.00	0.25
Initial conditions		
Fish stock	0.25	1.00
Labour force	0.50	0.50
Optimal harvest levels		
Years 0–5	55%	45%
Years 5–10	75%	35%
Years 10–15	75%	30%
Years 15–20	75%	40%
Years 20–30	75%	35%

Simulation Results

To examine the optimal bio-socio-economic dynamics of the fishery system, a simulation model was developed, based on equations (1) and (2), and using the specific functional forms in equations (17), (18), and (19). The simulation results focus on the effects of intrinsic growth rates (r,ρ), initial conditions and management objectives, with other parameters fixed at arbitrary values ($a=1$, $q=1$, $p=1$, $c=0.01$, $l=0$, $\tau=2$, $A=2.12$, $M=1$, and $\alpha=\beta=0.50$). The fish stock reproduction function $F(x)$ is given by a logistic of the form $F(x) = rx(1 - x/K)$, with the carrying capacity set at $K=1$.

Simulations with a 30-yr time horizon and a discount rate of $\delta=10\%$ were carried out by discretizing the continuous processes involved, using a time increment of $\Delta t = 0.1$ yr. The following specific assumptions were made:

(i) Only harvest management options resulting in a long-term sustainable fish stock are allowable (so that the sustainability and conservation of the resource represents a firm constraint).

(ii) Each harvest management option consists of a set of five harvest levels, one for each of: years 0–5, years 5–10, years 10–15, years 15–20, and years 20–30. (This assumption was made to reduce computational time, while still allowing dynamic complexity.)

(iii) The minimum overall income level $\pi+\tau$ is 0 in any period.

(iv) Fishing effort E cannot exceed the available labour force L; $E(t)\leq L(t)$ at each point in time.

(v) The per capita rate of decline in the labour force (and fishery population) cannot exceed 20% ($G\geq -0.20L$).

Two illustrative cases were examined. The first involved maximization of the sum of discounted rents (i.e. with $\lambda = 0$, $a_2=0$, $a_3=0$, and $a_4=0$ in equation (22)). Relatively fast adjustment dynamics and relatively small initial stock size and labour force were assumed. To allow recovery of the stock, the optimal harvest level in the first 5 yr was 55% (i.e. 55% of the carrying capacity K should be caught per year), increasing to an equilibrium level of 75% thereafter (see Table 2).

In fact, however, the actual harvest level in this case lies initially below its optimal level (55%), since fishing effort is

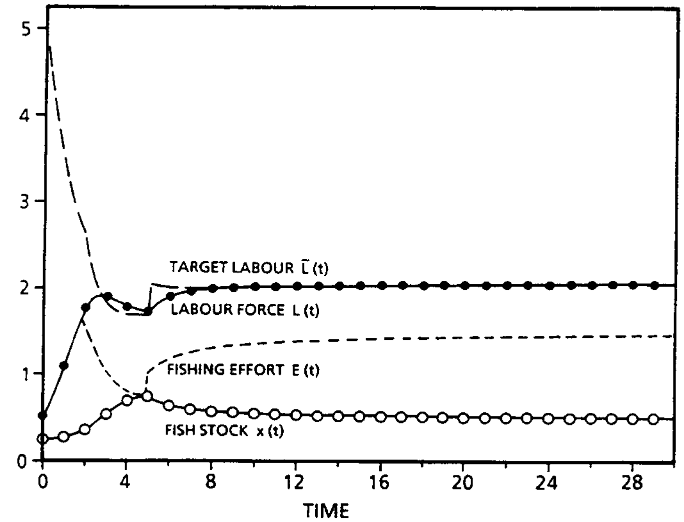

FIG. 2. Optimal dynamics of the fish stock $x(t)$, fishing effort $E(t)$, fishery labour $L(t)$, and the target labour force $\bar{L}(t)$, are shown for a 30-yr time horizon, with initial conditions $x(0)=0.25$ and $L(0)=0.50$. Maximum intrinsic growth rates are $r=3$ for the fish population and $\rho=1$ for the labour force. The optimal harvest level is 55% for the first 5 yr and 75% thereafter. Note that the constraint $E(t)\leq L(t)$ restricts the fishing effort, and hence the actual harvest level, in the first few years until the labour force has increased sufficiently.

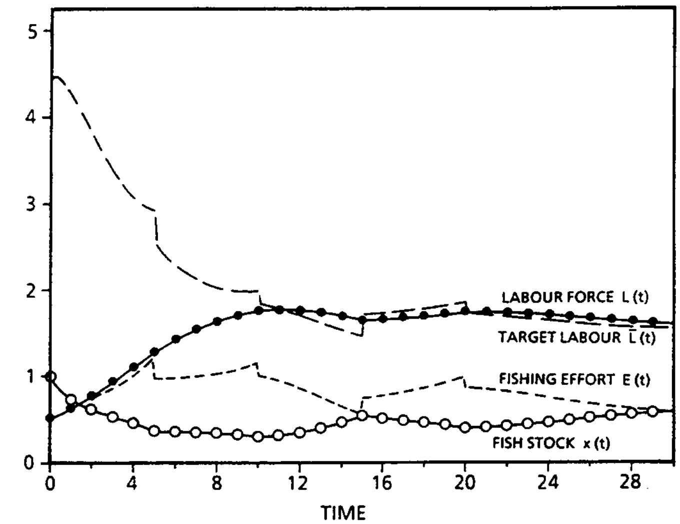

FIG. 3. The optimal dynamics of the fish stock $x(t)$, effort $E(t)$, labour $L(t)$, and the target labour force $\bar{L}(t)$, are shown for a 30-yr time horizon, with initial conditions $x(0)=1.00$ and $L(0)=0.50$. Maximum intrinsic growth rates of $r=1.5$ for the fish stock and $\rho=0.25$ for the labour force are lower than those used in Fig. 1, producing a more gradual approach to equilibrium. However shifts in the desired harvest level, which ranges from 45% to 35%, lead to periodic jumps in effort E and target labour $\bar{L}$, and corresponding disequilibrium dynamics in the labour force L.

constrained by the size of the labour force ($E\leq L$). This leads to an increase in the fish stock (see Fig. 2), while a high profit rate leads to gradual expansion in the labour force, and a corresponding increase in the fishing effort level. However, once the fish stock has grown to a certain extent, effort must decrease in order to maintain the desired harvest. When in year 5, the optimal rate of harvest changes from 55% to 75%, this produces jumps in both the effort and the natural labour force. Labour and the fish stock then gradually adjust towards a new long-term equilibrium.

The second case was based on maximizing the present value of the sum of rents (π) and direct labour benefits (δL), equally weighted (i.e. $\lambda=0$, $a_2=0$, $a_3=0$, and $a_4=a_1$ in equation (22)). Relatively slow dynamics and an initially large fish stock were assumed. In this case, the optimal harvest level changes to a greater extent over time (see Table 2), producing fluctuations in both the fish stock and the labour force. Initially, the large fish stock and low labour force produce incentives for entry into the fishery, indicated by the high natural labour force $\bar{L}(t)$. This leads to expansion of both $L(t)$ and the fishing effort $E(t)$ (see Fig. 3), a corresponding decline in the fish stock, and thus a decrease in the desirability of the fishery ($\bar{L}$). Eventually, the actual labour force (L) rises to meet its target level, and thereafter "tracks" changes in the target $\bar{L}$ caused by jumps in the harvest level.

Note that in both cases described above:

(i) since periodic jumps are assumed to occur in the harvest, the optimal fish stock dynamics are not monotonic, but rather under- and over-shooting of the eventual stock equilibrium can occur.

(ii) at every point in time, the labour force L approaches its target level, although this "tracking" is subject to delay.

While a basic drawback of simulation methods is the inability to draw general conclusions, it appears from these examples that dynamic behaviour can be quite complex in fishery systems involving labour adjustment processes. Furthermore, the existence of multiple objectives can significantly alter the desired management plans. For example, the multiobjective management goal analysed above, based on balancing income generation and community welfare considerations, produced optimal harvest levels that are initially somewhat higher than those obtained under otherwise identical conditions but with a simple rent-maximization goal (not shown). This result is in keeping with that found in the previous section, where the addition of positive labour benefits to the objective function produced a decrease in the equilibrium fish stock size.

Discussion

The models analysed in this paper represent an attempt to develop a framework for analysing the joint ecological and socio-economic dynamics inherent in fishery systems. This bio-socio-economic approach involves (1) the determination of appropriate adjustment processes to predict the response of fish stocks and of fishermen to changing conditions in the fishery, and (2) the use of these dynamics to undertake multiobjective management of fishery harvests. The size and stability of the labour force, the level of employment in the fishery-dependent economy, and the per capita income level are included explicitly along with rent maximization in the optimization process.

MGR equations were obtained to provide insights into the optimal equilibrium of the fishery system. These expressions indicate precisely how fish stock and labour dynamics interact to determine the tradeoffs between immediate benefits of harvesting the resource and future benefits of maintaining fish in the sea.

A comparison between the results for this bio-socio-economic model and those obtained from a simpler "bio-economic" analysis highlights the explicit effects on the optimal equilibrium due to the introduction of labour benefits into the management objective function. Using specific forms for the fishery production function, the economic rents function, and the dynamics, it was found that adding labour components to the objective decreases (increases) the optimal equilibrium fish stock if the marginal benefits of labour are positive (negative). This result, while apparently intuitive, in fact depends to some extent on the nature of the model – further research will be required to determine its robustness to a variety of possible dynamic assumptions.

The approach to equilibrium has also been analysed, using computer simulation. This shows clearly the dynamics of both the labour force and its target or "natural" level, together with the gradual adjustment of the former to the latter. Under optimal management, harvest levels were found to vary substantially over time (although this is in part due to the 5-yr steps assumed in our analysis). Labour dynamics can depend significantly on the constraints placed on fishing effort, if for example effort is restricted by the size of the labour force itself.

This paper has emphasized optimization approaches, with fishing effort chosen optimally subject to constraints on the available labour supply. The study of resource, labour, and community dynamics could also be undertaken using behavioral modelling approaches, in which fishing effort dynamics are based on behavioral assumptions rather than optimization. For example, Smith (1968) assumes that the time rate of change in fishing effort $E(t)$ is proportional to the difference between current fishery rents (π) and a base level ($\bar{\pi}$), perhaps representing the possible profit in alternative economic activities. Hence, in the Smith model, high rents lead to increased effort, while low (or negative) rents lead to a reduction in effort. (This behaviour with respect to fishery rents is similar to that assumed for the labour force in the present model, but we are differentiating here between the labour force per se, and the effort it is actually able to exert in the fishery.)

Of course, this is but one possible assumption about the determinants of fishing behaviour. It is also possible that fishermen might adjust their collective fishing effort in order to fully utilize available labour and capital inputs, or to maintain either constant fishery rents or fishermen incomes. Alternatively, fishery management may set a constant effort or constant harvest rate strategy (such as the "$F_{0.1}$" approach used for groundfish stocks on Canada's Atlantic coast). In either case, managers may control the fishery only through a total allowable catch quota, while fishermen will respond by setting their desired effort levels. From a research point of view, the modelling approach presented here has the flexibility to allow a comparison amongst these various possible effort strategies, and the resulting labour dynamics. Such behavioral models will be examined in detail in a future paper.

The application of any fishery model to specific cases requires the collection of suitable data to "fit" the model. In the case of bio-socio-economic models, it is necessary to assemble time series of data on fishery labour forces, fishing community populations, and fishery participation rates (e.g. Copes 1983), as well as data on fish stock dynamics and economic parameters. While the information needs are great, it is also true that in most fisheries, efforts to date have not been sufficient in collecting and consolidating existing data in preparation for an integrated analysis of the fishery system. The modelling framework developed here may be of use in highlighting the information requirements needed to undertake such an analysis.

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References

Andersen, R. 1978. The need for human sciences research in Atlantic coast fisheries. J. Fish. Res. Board Can. 35:1031–1049.

Bishop, R. C., D. W. Bromley, and S. Langdon. 1981. Implementing multiobjective management of commercial fisheries: a strategy for policy-relevant research. *In* L. G. Anderson [ed.] Economic analysis for fisheries management plans. Ann Arbor Science. Ann Arbor, MI.

Charles, A. T. 1983. Optimal fisheries investment: comparative dynamics for a deterministic seasonal fishery. Can. J. Fish. Aquat. Sci. 40:2069–2079.

1988. Fishery socioeconomics: a survey. Land Econ. 68:276–295.

Christy, F. T., and A. D. Scott. 1965. The common wealth in ocean fisheries. Johns Hopkins University Press, Baltimore, MD.

Clark, C. W. 1976. Mathematical bioeconomics: the optimal management of renewable resources. Wiley-Interscience, New York, NY. 352 p.

Clark, C. W., and G. R. Munro. 1975. Economics of fishing and modern capital theory: a simplified approach, J. Environ. Econ. Manage. 2:92–106.

Copes, P. 1983. Fisheries management on Canada's Atlantic coast: economic factors and socio-political constraints. Can. J. of Region. Sci. 6:1–32.

Doeringer, P. B., P. I. Moss, and D. G. Terkla. 1986. The New England fishing economy: jobs, income, and kinship. University of Massachusetts Press, Amherst, MA. 147 p.

FAO. (Food and Agricultural Organization). 1983. Report of the expert consultation on the regulation of fishing effort (fishing mortality). FAO Fish. Rep. 289, Rome, 34 p.

Healey, M. C. 1984. Multiattribute analysis and the concept of optimum yield. Can. J. Fish. Aquat. Sci. 41:1393–1406.

Hilborn, R. 1985. Fleet dynamics and individual variation: Why some fishermen catch more fish than others. Can. J. Fish. Aquat. Sci. 42:2–13.

Hilborn, R., and C. J. Walters. 1977. Differing goals of salmon management on the Skeena River. J. Fish. Res. Board Can. 34:64–72.

Kamien, M. I., and N. L. Schwartz. 1981. Dynamic optimization: The calculus of variations and optimal control in economics and management. North Holland, New York, NY.

Keeney, R. L. 1977. A utility function for examining policy affecting salmon on the Skeena River. J. Fish. Res. Board Can. 34:49–63.

Krauthamer, J. T., W. E. Grant, and W. L. Griffin. 1987. A sociobioeconomic model: the Texas inshore shrimp fishery. Ecol. Model. 35: 275–307.

Lawson, R. 1984. Economics of fisheries development, Frances Pinter Publishers, London, 283 p.

Munro, G. R. 1976. Applications to policy problems: an example. *In* C.W. Clark, Mathematical bioeconomics: the optimal management of renewable resources. Wiley-Interscience, New York, NY.

Opaluch, J. J., and N. E. Bockstael. 1984. Behavioral modelling and fisheries management, Mar. Res. Econ. 1:105–115.

Panayotou, T. 1982. Management concepts for small-scale fisheries: economic and social aspects. FAO Fish. Tech. Pap. No. 228.

Panayotou, T., and D. Panayotou. 1986. Occupational and geographical mobility in and out of Thai fisheries. FAO Fish. Tech. Pap. 271:77p.

Pringle, J. D. 1985. The human factor in fishery resource management. Can. J. Fish. Aquat. Sci. 42:389–392.

Regier, H. A., and A. P. Grima. 1985. Fishery resource allocation: an exploratory essay. Can. J. Fish. Aquat. Sci. 42:845–859.

Smith, I. R. 1981. Improving fishing incomes when resources are overfished. Mar. Policy 5:17–22.

Smith, V. L. 1968. Economics of production from natural resources. Am. Econ. Rev. 58:409–431.

Terkla, D. G., P. B. Doeringer, and P. I. Moss. 1985. Common property resource management with sticky labor: the effects of job attachment on fisheries management. Discussion Pap. No. 108, Department of Economics, Boston University, ME.