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Lectures on the Economics of Fisheries Production

By
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LECTURES ON

THE ECONOMICS OF FISHERIES

PRODUCTION*

by

JON CONRAD, DALE SQUIRES, JIM KIRKLEY+

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PREFACE

During the past 10 years, there has been a significant increase in 1) the number of economists interested in commercial fishing and 2) the number of fisheries scientists interested in economics. The economics profession has been stimulated by the development of bioeconomic models which seek to maximize some measure of fishery performance subject to an equation (or equations) describing the dynamics of the fish stock (or stocks). At the same time, economists have expanded their ability to model and estimate production relationships; that is, the technological relationships between inputs and outputs. Fisheries scientists, particularly those concerned with the management of commercial stocks, are more aware of the importance of economics in both formulating management objectives and in predicting how fishermen might respond to specific management policies.

These lectures are an attempt to review the relatively recent advances in dynamic modeling and production theory as they relate to the economic management of single- and multiple-species fisheries. They will also assess the impediments to applying modern production theory when estimating bioeconomic parameters.

In the first lecture Jon Conrad reviews the relationship between 1) the production function, 2) the growth function, and 3) the yield-effort function for the single species fishery and extends these concepts to the multispecies fishery using the multiple output production function. The promise and problems inherent with duality-based approaches to estimating bioeconomic parameters are briefly discussed.

In the second lecture Dale Squires reviews the early literature on fisheries production and examines in greater detail the assumptions underlying duality-based estimation techniques as they relate to multispecies production.

In the third lecture Jim Kirkley discusses his recent empirical work on the New England trawler fleet. While the landings of individual species are aggregated into a single output index, two measures of effort are employed, and factor shares from the 'econometric analysis are compared with the results obtained from a cost simulator.

A common theme running through all three lectures is the need for better data, particularly input and cost data, if duality-based theory is to be successfully applied to multispecies fisheries. With a better understanding of models and methods, it is hoped that economists within the NMFS and academia might be more effective in working together to establish the data base necessary for modern production analysis. Such analysis seems necessary, though not sufficient, for rational fisheries management.

Dr. Richard Marasco

Lecture Coordinator

CONTENTS

PRODUCTION IN SINGLE AND MULTISPECIES

FISHERIES: A BIOECONOMIC PERSPECTIVE

by

Jon Conrad

INTRODUCTION AND OVERVIEW

This lecture is concerned with the bioeconomic relationships between (1) the production function, [2) the growth function(s), and 3) the yield-effort function in single and multispecies fisheries. A clear understanding of these relationships is important for both the empirical analysis of fisheries production as well as the broader question of resource management.

In the next section, these relationships are reviewed for the single species fishery. The form of the production, growth, and derived yield-effort functions are presented for the Gordon-Schaefer model and a model employed by Spence (1974). Equations for optimal stock levels for each model are given based on a discrete control problem which maximizes the present value of net revenues.

In the third section, a multispecies problem is formulated where production is characterized by a multiple-output production function and growth by a dynamical system which allows for species interaction. The multiple-output production function is a more general approach than that employed by Agnello and Anderson (1977). Parameters of a derived or presumed yield-effort function might be estimated employing duality-based profit, revenue, or cost functions. As in the single species case, a knowledge of parameters of the production and growth functions alone are not adequate for identifying optimal levels for effort, stocks, and yields. A multispecies optimization problem is formulated, and the equations defining the steady-state optimum are derived.

The final section discusses some of the obstacles to estimating parameters of a multispecies yield-effort function using duality-based relationships. The obstacles are seen to be primarily data-related and hinge on our ability to develop suitable indices for landings and especially effort which are distinct econometrically, and for which appropriate price and cost data exist or may be constructed.

PRODUCTION FUNCTIONS AND YIELD-EFFORT CURVES IN THE BASIC BIOECONOMIC MODEL

Much of the received wisdom in fisheries economics is based on a simple bioeconomic model where the population or stock of the species of interest is measured by a single variable, usually denoted as X_t. The units of measurement might be the number of individuals in the population at time t or more typically population biomass, perhaps measured in metric tons. Characterization of the stock by a single variable greatly facilitates the modeling of biological and economic processes, but it precludes consideration of sex or age related attributes of the population.

The inputs of the fishing firm or industry are assumed capable of aggregation into a single input called effort, denoted as Et. Number of boats, vessel days, or standard days at sea (where vessel power is taken into account) are common measures of effort.

Effort is directed at the fish stock resulting in harvest or yield, denoted as Y_t. We might represent the production function of the vessel or industry in a general implicit form as

$$H(E_t, X_t, Y_t) = 0. \tag{1}$$

Economic convention is such that

$$\frac{\partial H(\cdot)}{\partial E_t} > 0 , \frac{\partial H(\cdot)}{\partial X_t} > 0 \text{ , and } \frac{\partial H(\cdot)}{\partial Y_t} < 0 ,$$

and H (•) is assumed to define an efficient input-output combination, in that, given a level for effort and stock, H(•) specifies the 'maximum amount of Y_t

and conversely, given a level for stock and yield, H (•) specifies the minimum amount of E_t.

The fish stock is assumed to change according to

$$X_{t+1} = X_t + F(X_t) - Y_t \ , \qquad (2)$$

where $F(X_t)$ describes the net effect of natural growth and mortality and Y_t (yield) corresponds to fishing mortality.

It is not usually possible to estimate the parameters of H(•) and F(•) directly. For most species there are insufficient data on estimates of X_t. Biologists and economists have often sought to estimate the parameters of the production and growth functions via estimation of a yield-effort curve. The yield-effort curve is a steady-state (equilibrium) concept. In steady state, effort, stocks, and yield are unchanging through time ($Et = E$, $X_t = X$, and $Y_t = Y$ for all future t) and the system is in equilibrium.

In steady state, equation (2) implies that

$$Y = F(X) \ , \qquad (3)$$

or yield is equal to net natural growth. Suppose we can solve equation (3) for X as a function of Y such that

$$X = G(Y) \ . \qquad (4)$$

Substituting equation (4) into the production function (equation (1)) yields

$$H(E, G(Y), Y) = 0 \ , \qquad (5)$$

which may be defined as the implicit yield-effort curve. It is often possible to-solve equation (5) for the explicit yield-effort curve

$$Y = M(E) \ . \qquad (6)$$

At this, point it might be helpful to examine the production, growth, and yield-effort curves for some specific models. We will look at two models. The first is associated with the work of Gordon (1954) and Schaefer (1957) and is referred to as the Gordon-Schaefer model by Clark (1976). In this model the production function takes a Cobb-Douglas (1928) form

$$Y_t = qE_tX_t \ , \tag{7}$$

where q is referred to as the catchability coefficient. This form results from the assumption that catch per unit effort (CPUE) is proportional to stock. This production function exhibits unitary yield-effort and substitution (effort-stock) elasticities.

The growth function in the Gordon-Schaefer model assumes a logistic form such that

$$X_{t+1} = X_t + rX_t(1 - X_t/K) - Y_t \ , \tag{8}$$

where. r is referred to as the intrinsic growth rate and K is the environmental carrying capacity.

In steady state,

$$Y = rX(1 - X/K) \ . \tag{9}$$

Instead of solving equation (9) for X as a function of Y, we note that

$$rX(1 - X/K) = gEX \ . \tag{10}$$

Dividing both sides of equation (10) by X, we can solve for X as a function of E, which upon substitution in equation (7) yields the (explicit) yield-effort curve

$$Y = M(E) = qKE(1 - qE/r) \ . \tag{11}$$

The second model to be discussed was employed by Spence (1974) in a bioeconomic study of the blue whale. Spence criticized the Cobb-Douglas form as a fisheries production function because for high values of effort it was possible to obtain yields in excess of stock, that is, as $E_t \to \infty$, $Y_t > X_t$. As an alternative form, Spence suggests a growth function where next year's stock is determined by

$$X_{t+1} = F(X_+) - Y_+ = AX_+^a - Y_+ \ , \tag{12}$$

and where the production function takes the form

$$Y_t = F(X_t)\,[1 - e^{-bE_t}] = AX_t^a\,[1 - e^{-bE_t}]\,. \qquad (13)$$

This production function defines yield as a proportion of next year's stock, and as $E_t \to \infty$, $Y_t \to F(X_t)$ and $X_{t+1} \to 0$. Substituting (13) into (12) implies $X_{t+1} = AX_t^a e^{-bE_t}$. Evaluating this expression at steady state, solving for X, and substituting back into (13) will yield the (explicit) yield-effort curve

$$Y = M(E) = (Ae^{-abE})^{=}\ (1-e^{-bE}). \qquad (14)$$

In summary, single species biomass models will include a production function relating yield to stock and effort, and a difference (or differential) equation describing how the stock changes as a result of net natural growth and fishing. In steady-state equilibrium, the production and growth functions may be solved for the yield-effort curve. This latter relationship is often used to estimate various bioeconomic parameters based only on catch-and-effort data. Fox (1975) describes an empirical technique for estimating growth and production parameters using ordinary least squares (OLS) and an integral estimator. This approach, like most empirical studies in economics,. presumes that the data represent equilibria at each point in time. This assumption is often untenable for fisheries responding to rapidly changing economic conditions or environmental perturbations. Estimation of parameters for partially adjusted (disequilibrium) systems will typically involve lag structures that may require more complex econometric techniques, a topic which is beyond the scope of this lecture.

If parameter estimates of the underlying growth and production functions can be obtained from estimates of parameters of the yield-effort curve, can the economist pack his bags and go home? If one wishes to identify anything more than maximum sustainable yield (MSY), the answer is no. In particular, if the economist wishes to estimate the bioeconomic optimum, he or she will need to identify parameters of the revenue and cost functions and select an appropriate discount rate,.

For the basic bioeconomic model we might specify a dynamic optimization problem which seeks to maximize the present value of net revenues subject to the equation describing population dynamics. For the Gordon-Schaefer model this problem takes the form

$$\max_{\{Y_t\}} \quad N = \sum_{t=0}^{\infty} \rho^t \,[p - c/qX_t]Y_t \qquad \text{subject to}$$

$$X_{t+1} = X_t + rX_t(1 - X_t/K) - Y_t \,, \tag{15}$$

where p is the unit price of fish, c is the unit cost of effort, and $\rho = 1/(1 + \delta)$, where δ is the per period discount rate. The problem may be solved by forming the Lagrangian

$$L = \sum_{t=0}^{\infty} \rho^t \left\{[p - c/qX_t]Y_t + \rho\lambda_{t+1}\,[X_t + rX_t(1 - X_t/K) - Y_t - X_{t+1}]\right\} . \tag{16}$$

Evaluating the first order conditions in steady state, one obtains a system of three equations in three unknown (Y, X, A). Eliminating Y and A via substitution, one will obtain a quadratic in X, with the positive root equaling the optimal stock; that is,

$$X^* = \frac{K}{4}\left[\left(\frac{c}{qpK} + 1 - \frac{\delta}{r}\right) + \sqrt{\left(\frac{c}{qpK} + 1 - \frac{\delta}{r}\right)^2 + \frac{8c\delta}{qpKr}}\,\right] . \tag{17}$$

Optimal stock will depend. not only on r, K, and q (param-eters of the production and growth functions), but also on c, p, and δ.

For Spence's model of the blue whale the Lagrangian takes the form

$$L = \sum_{t=0}^{\infty} \rho^t \left\{pAX_t^a \,[1 - e^{-bE_t}] - cE_t + \rho\lambda_{t+1}\,[AX_t^a e^{-bE_t} - X_{t+1}]\right\} . \tag{18}$$

Using the same procedure, that is, obtaining the first order conditions, evaluating them in steady state, and eliminating Y and X by substitution, Conrad (1982) obtains the equation

$$\frac{abAX^{a} - a(c/p)}{[bX - c/p]} = (1 + \delta) . \tag{19}$$

This is a single equation in X with bioeconomic parameters a, A, b, c, p, and 6. If one has estimates (or assigned values) for these parameters, one can iteratively solve equation (19) for the optimal stock X*.

The principal conclusions of this section might be summarized as follows:

1. The basic bioeconomic model is a single species model which presumes that stock can be measured by a single variable X_t and effort can be represented by a single measure Et.

2. By evaluating the growth and production functions in steady state, one can in general derive a yield-effort curve. This curve is empirically important because it may allow one to estimate parameters of the growth and production functions based only on yield and effort data.

3. While estimates of the parameters of the yield-effort curve may allow one to identify MSY, identification of the bioeconomic optimum will require formulation of an appropriate dynamic optimization problem and solution of the first order conditions in steady state. In general, the optimal stock will depend on parameters of the production function, growth function, price, cost, and the discount rate.

THE MULTISPECIES FISHERY AND MULTIPLE-OUTPUT PRODUCTION

The basic bioeconomic model may be a reasonable paradigm for a fishery where gear is perfectly selective and where all environmental influences are accounted for in the growth function $F(X_t)$. In many fisheries perfect gear selectivity is not possible, and a unit of effort will result in a yield of several species. Further, the various species may exert dynamic influences on one anotherand thus the harvest of one species will indirectly influence the dynamics of the others. These conditions lead to production functions involving multiple inputs and multiple outputs, as well as multispecies dynamics.

To make this problem less abstract and to set the stage for subsequent sections, consider the following problem:

> Three species of groundfish, cod ($X_{1,t}$), haddock ($X_{2,t}$), and flounder ($X_{3,t}$) are harvested by two non-selective gear types ($E_{1,t}$) and ($E_{2,t}$). The three species may exhibit interspecific effects. 1) How can we conceptualize the relationships between stocks, yields, and fishing effort; 2) how might we estimate the parameters of these relationships; and 3) how should such a system be managed?

From the perspective of fisheries production, we are dealing with three outputs; yields of cod, haddock, and flounder ($Y_{1,t}$, $Y_{2,t}$, $Y_{3,t}$), and five inputs; two endogenous effort inputs ($E_{1,t}$, $E_{2,t}$), and three exogenous stock inputs ($X_{1,t}$, $X_{2,t}$, $X_{3,t}$). The relationship between inputs and outputs may be represented in general by a single production function written implicitly as

$$H(E_{1,t}, E_{2,t}; X_{1,t}, X_{2,t}, X_{3,t}; Y_{1,t}, Y_{2,t}, Y_{3,t}) = 0. \tag{20}$$

Resource dynamics may be represented by the following dynamical system:

$$\begin{aligned} X_{1,t+1} &= X_{1,t} + F_1(X_{1,t}, X_{2,t}, X_{3,t}) - Y_{1,t}, \\ X_{2,t+1} &= X_{2,t} + F_2(X_{1,t}, X_{2,t}, X_{3,t}) - Y_{2,t}, \text{ and} \\ X_{3,t+1} &= X_{3,t} + F_3(X_{1,t}, X_{2,t}, X_{3,t}) - Y_{3,t}, \end{aligned} \tag{21}$$

We may be able to derive a multispecies yield-effort function in a fashion similar to that employed in the single species model. In steady state, $Y_1 = F_1(\bullet)$, $Y_2 = F_2(\bullet)$, and $Y_3 = F_3(\bullet)$. If these equations can be solved for the system

$$X_1 = G_1(Y_1,\ Y_2,\ Y_3)\ ,$$
$$X_2 = G_2(Y_1,\ Y_2,\ Y_3)\ , \qquad (22)$$
$$X_3 = G_3(Y_1,\ Y_2,\ Y_3)\ ,$$

then substitution of equation (22) into equation. (20) will give the (implicit) multispecies yield-effort function

$$H(E_1,\ E_2;\ G_1(\cdot),\ G_2(\cdot),\ G_3(\cdot);\ Y_1,\ Y_2,\ Y_3) = 0 \qquad (23).$$

The ability to solve the steady state growth functions for a system such as equation (22) will depend on the existence and the form used to characterize multispecies interaction. For a model with multispecies production characterized by

$$Y_{1,t} = (q_{1,1}E_{1,t} + q_{1,2}E_{2,t})\ X_{1,t},$$
$$Y_{2,t} = (q_{2,1}E_{1,t} + q_{2,2}E_{2,t})\ X_{2,t}, \qquad (24)$$
$$Y_{3,t} = (q_{3,1}E_{1,t} + q_{3,2}E_{2,t})\ X_{3,t},$$

and with population dynamics of the form

$$X_{1,t+1} = X_{1,t} + r_1X_{1,t}(1 - X_{1,t}/K_1) + a_1X_{1,t}X_{2,t} + b_1X_{1,t}X_{3,t} - Y_{1,t}\ ,$$
$$X_{2,t+1} = X_{2,t} + r_2X_{2,t}(1 - X_{2,t}/K_2) + a_2X_{1,t}X_{2,t} + b_2X_{2,t}X_{3,t} - Y_{2,t}\ ,$$
$$X_{3,t+1} = X_{3,t} + r_3X_{3,t}(1 - X_{3,t}/K_3) + a_3X_{1,t}X_{3,t} + b_3X_{2,t}X_{3,t} - Y_{3,t}\ ,$$
$$(25)$$

Agnello and Anderson (1977) derive a system of directed and by-catch equations for each species which will sum to its yield-effort function.

If suitable growth functions can be identified which allow for derivation of the implicit yield-effort function, then the next step toward estimation entails the specification of H(•), the production function. For our two effort-three species example we could examine a variety of forms employing various degrees of separability between effort levels, stocks, and yields. Hasenkamp (1976) examines various combinations of Cobb-Douglas (CD), constant elasticity of substitution (CES), constant elasticity of transformation (CET), and the more flexible quadratic (DQ) and generalized (GQ) forms suggested by Christensen et al. (1973) and Diewert (1973, 1974). In 'examining potential combinations that might be used to specify the multispecies production function $H(\bullet)$, one might start by assuming that

$$H(\bullet) = f(\bullet) - [g_1(\bullet)h_1(\bullet)+g_2(\bullet)h_2(\bullet)] = 0 \tag{26}$$

where

$f(\bullet) = f(Y_{1,t}, Y_{2,t}, Y_{3,t})$ is an output or yield function,

$g_1(\cdot) = g_1(X_{1,t}, X_{2,t}, X_{3,t})$ is a stock function associated with" gear type (effort) $E_{1,t}$,

$g_2(\cdot) = g_2(X_{1,t}, X_{2,t}, X_{3,t})$ is a stock function associated with gear type (effort) $E_{2,t}$,

$h_1(\bullet) = h_1 (E_{1,t})$ is an effort function for gear 'type one, and

$h_2(\bullet) = h_2(E_{2,t})$ is an effort function for gear type two.

Equation (26) assumes that the multispecies production function is separable into an output function and two expressions' involving the product of stock and effort functions for each gear type. The latter expressions assume that the gear types do not directly interact. For example, in steady state a CET output function coupled with a set of CD input functions would result in

$$H(\cdot) = \left(\sum_{j=1}^{3} \gamma_j Y_j^{\eta}\right)^{\frac{1}{\eta}} - [(\alpha_{1,1}X_1^{\beta_{1,1}} + \alpha_{1,2}X_2^{\beta_{1,2}} + \alpha_{1,3}X_3^{\beta_{1,3}})E_1^{\beta_1} + (\alpha_{2,1}X_1^{\beta_{2,1}} + \alpha_{2,2}X_2^{\beta_{2,2}} + \alpha_{2,3}X_3^{\beta_{2,3}})E_2^{\beta_2}] \,. \tag{27}$$

Other combinations are possible. Hasenkamp (1976) also notes necessary parameter normalizations and homogeneity restrictions. In combination with a set of "stock-solving" growth functions, the multispecies production function would permit one to derive the yield-effort function. Would the parameters of 'the yield-effort function be amenable to estimation? Because of nonlinearity in most multispecies growth equations, the answer is probably no. An alternative to the derived function is to presume that the yield-effort relationship takes a particular form and abandon any attempt at relating parameters of the yield-effort curve to the underlying parameters of the growth and production functions. Elasticities of economic importance might still be identified by directly specifying

$$H(E_1, E_2; Y_1, Y_2, Y_3) = 0 , \tag{28}$$

where $H(\cdot)$ is the presumed yield-effort function in contrast to the derived yield-effort function of equation (23). The presumed yield-effort function is a multiple-output function which in our example involves two effort inputs. As with the multispecies production function, $H(\cdot)$ might be specified using a variety of forms (CD, CES, CET, DQ, and GQ) involving various degrees of separability between effort levels and yields.

Parameters of the presumed yield-effort function may be estimated directly or indirectly using duality theory. Consider the industry comprised of vessels which at each point in time seek to maximize net revenues subject to the presumed yield-effort function. Letting $p_{j,t}$ be the price per unit for species j and $c_{i,t}$ be the cost per unit for effort i, then maximization of static net revenue may be accomplished by forming the Lagrangian

$$L = \sum_{j=1}^{3} p_{j,t}Y_{j,t} - \sum_{i=1}^{2} c_{i,t}E_{i,t} - \lambda_t\tilde{H}(\cdot) , \tag{29}$$

and requires

$$\frac{\partial L}{\partial Y_{j,t}} = p_{j,t} - \lambda_t\frac{\partial \tilde{H}(\cdot)}{\partial Y_{j,t}} = 0 , \tag{30}$$

$$\frac{\partial L}{\partial E_{i,t}} = -c_{i,t} - \lambda_t\frac{\partial \tilde{H}(\cdot)}{\partial E_{i,t}} = 0 , \tag{31}$$

$$\frac{\partial L}{\partial \lambda_t} = - \tilde{H}(\cdot) = 0 . \tag{32}$$

Second order conditions require that H(•) be convex around the effort-yield values satisfying the first order conditions. To ensure this condition for all possible sets of optimal (E_t, Y_t), global convexity of H(•) is presumed requiring that the Hessian $\partial^2 H(\cdot)/\partial(\cdot)\partial(\cdot)$ be positive semidefinite. If the Hessian is nonsingular at the net revenue maximizing yield-effort values, then we can solve the first order conditions (30) - (32) for the equations

$$Y^*_{j,t} = y_j(p_{1,t}, p_{2,t}, p_{3,t}; c_{1,t}, c_{2,t}) \text{ , } j = 1, 2, 3 \text{ ,} \qquad (33)$$

$$E^*_{j,t} = e_i(p_{1,t}, p_{2,t}, p_{3,t}; c_{1,t}, c_{2,t}) \text{ , } i = 1, 2 \text{ ,} \qquad (34)$$

$$\lambda^*_t = \lambda_t(p_{1,t}, p_{2,t}, p_{3,t}; c_{1,t}, c_{2,t}) \text{ ,} \qquad (35)$$

where $y_j(\bullet)$ is the static supply function for the j^{th} species; $e_i(\bullet)$ is the effort demand function for the i^{th} gear type; and $\lambda_t(\cdot)$ is a shadow price function.

Using functions (33) and (34) we may define the net revenue or profit function as

$$N^*_t = N(p_{1,t}, p_{2,t}, p_{3,t}; c_{1,t}, c_{2,t}) = \sum_{j=1}^{3} p_{j,t} y_j(\cdot) - \sum_{i=1}^{2} c_{i,t} e_i(\cdot) \text{ ,} \qquad (36)$$

which gives the value of maximized static profit, conditional on per unit species prices $p_{j,t}$ and per unit effort costs $c_{i,t}$. The now famous lemma by Shepart (1970) states that the partial derivative of the profit function with respect to the j^{th} output price yields the j^{th} output (species) supply function, while the partial derivative with respect to the ith input price yields the negative of the i^{th} input (effort level) demand function.

Duality theory permits the economist to estimate certain parameters of the production function (or in our case the presumed yield-effort function) based on the observed changes in inputs (effort) and outputs (species yield) resulting from changes in input and output prices. The firm or industry is assumed to behave optimally and to have achieved the optimal input-output mix at each point in time; that is, equations (33) and (34) must hold for an industry through time or for each firm at a particular point in time. The parameters of interest will often include returns. to scale, elasticities of substitution (between inputs), and elasticities of transformation (between outputs).

A more detailed discussion of duality-based econometric techniques and their potential application to estimation of parameters of a presumed yield-effort function will be discussed in the next lecture. It is important to emphasize, as we did for the single species model, that optimal management of a multispecies system must be based on more than a knowledge of parameters of a presumed or derived yield-'effort function. Optimal bioeconomic management requires formulation of a suitable dynamic optimization problem. Assuming species prices and unit costs are constant (i.e., the "small fishery" assumption), we might formulate the multispecies management problem as one which seeks a saddle point to the Lagrangian

$$L = \sum_{t=0}^{\infty} \rho^t \left\{ \sum_{j=1}^{3} p_{j,t} Y_{j,t} - \sum_{i=1}^{2} c_{i,t} E_{i,t} - \mu_t H(\cdot) + \rho \sum_{j=1}^{3} \lambda_{j,t+1} [X_{j,t} + F_j(\cdot) - Y_{j,t} - X_{j,t+1}] \right\} \quad . \tag{37}$$

for $E_{i,t}$, $X_{j,t}$, and $Y_{j,t}$ positive, the first order conditions require

$$\frac{\partial L}{\partial Y_{j,t}} = \rho^t \left\{ p_{j,t} - \mu_t \frac{\partial H(\cdot)}{\partial Y_{j,t}} - \rho \lambda_{j,t+1} \right\} = 0 \text{ , } j = 1, 2, 3, \tag{38}$$

$$\frac{\partial L}{\partial E_{i,t}} = \rho^t \left\{ -c_{i,t} - \mu_t \frac{\partial H(\cdot)}{\partial E_{i,t}} \right\} = 0 \text{ , } i = 1, 2, \tag{39}$$

$$\frac{\partial L}{\partial X_{j,t}} = \rho^{t}\left\{-\mu_{t}\frac{\partial H(\cdot)}{\partial X_{j,t}} + \rho\lambda_{j,t+1} + \rho\sum_{k=1}^{3}\lambda_{k,t+1}\frac{\partial F_{k}(\cdot)}{X_{j,t}}\right\} - \rho^{t}\lambda_{j,t} = 0,$$

$$j = 1,\ 2,\ 3; \qquad k = 1,\ 2,\ 3, \tag{40}$$

$$\frac{\partial L}{\partial \mu_{t}} = \rho^{t}\left\{H(\cdot)\right\} = 0\ , \tag{41}$$

$$\frac{\partial L}{\partial \lambda_{j,t+1}} = \rho^{t+1}\left\{X_{j,t} + F_{j}(\cdot) - Y_{j,t} - X_{j,t+1}\right\} = 0\ ,\ j = 1\ ,\ 2\ ,\ 3\ , \tag{42}$$

For any two species, equation (38) requires

$$\frac{\dfrac{\partial H(\cdot)}{\partial Y_{j,t}}}{\dfrac{\partial H(\cdot)}{\partial Y_{k,t}}} = \frac{p_{j,t} - \rho\lambda_{j,t+1}}{p_{k,t} - \rho\lambda_{k,t+1}}\ , \tag{43}$$

or that the marginal rate of transformation of $Y_{j,t}$ for $Y_{k,t}$ be equated to the ratio of net prices, where the net price of species j in period t equals the market price ($p_{j,t}$) less user cost ($\rho\lambda_{j,t+1}$).

Equation (39) requires

$$\frac{\dfrac{\partial H(\cdot)}{\partial E_{1,t}}}{\dfrac{\partial H(\cdot)}{\partial E_{2,t}}} = \frac{c_{1,t}}{c_{2,t}}\ , \tag{44}$$

which is the familiar equilibrium condition for the firm that the rate of technical substitution of $E_{1,t}$ for $E_{2,t}$ will be equated to the ratio of input prices.

Equation (40) may be rewritten as

$$\lambda_{j,t} = -\mu_{t}\frac{\partial H(\cdot)}{\partial X_{j,t}} + \rho\lambda_{j,t+1} + \rho\sum_{k=1}^{3}\lambda_{k,t+1}\frac{\partial F_{k}(\cdot)}{\partial X_{j,t}}\ . \tag{45}$$

The variable (or value) $x_{j,t}$ is the shadow price for a unit of the j^{th} species in the water in period t. Over time we wish to maintain the stock of the j^{th} species so that its shadow price equals the sum of 1) its marginal value product in current production ($-\mu_t \frac{\partial H(\cdot)}{\partial X_{j,t}}$), 2) the discounted value of an additional unit of stock in the next period ($\rho\lambda_{j,t+1}$), and 3) the net value of marginal growth and interspecific effects ($\rho \sum_{k=1}^{3} \lambda_{k,t+1} \frac{\partial F_k(\cdot)}{\partial X_{j,t}}$). This last term might be negative. If an additional unit of species j reduced the growth of commercially valuable species k, then $\partial F_k(\cdot) / \partial X_{j,t} < 0$ and the sum over all species could be negative. In the optimally managed multispecies fishery, this may create an incentive to harvest species j at an economic loss if that loss could be more than recouped by larger stocks and harvests from species with a higher net value.

In steady state, equations (38) - (42) become

$$p_j - \rho\lambda_j = \frac{\partial H(\cdot)}{\partial Y_j}, \quad j = 1, 2, 3, \tag{46}$$

$$-\frac{\partial H(\cdot)}{\partial E_i} = c_i, \quad i = 1, 2, \tag{47}$$

$$\lambda_j = -\frac{\partial H(\cdot)}{\partial X_j} + \rho\lambda_j + \rho \sum_{k=1}^{3} \lambda_k \frac{\partial F_k(\cdot)}{\partial X_j}, \quad j = 1, 2, 3;\ k = 1, 2, 3, \tag{48}$$

$$H(\cdot) = 0, \tag{49}$$

$$Y_j = F_j(\cdot), \quad j = 1, 2, 3, \tag{50}$$

and constitute a system of 12 equations in 12 unknowns: E_1, E_2; X_1, X_2, X_3; Y_1, Y_2, Y_3; λ_1, λ_2, λ_3; and μ. Substitution may allow one to eliminate variables and reduce the system to a smaller dimension. Recall in the single species model that a single equation in X* was derived for the Gordon-Schaefer model and for the Spence model (see equations (17) and (19), respectively). To the author's knowledge there has been no analysis of a multispecies system such as that described by equations (46) - (50), and the solution and stability of this system for p_j, c_i, δ, $H(\cdot)$, and $F_j(\cdot)$ is an unsolved problem.

This section might be summarized as follows:

1. A multispecies fishery may be described by a) a -multiple-output production function with effort levels, stocks, and yields as arguments, and b) a dynamical system which includes the possibility of interspecific effects (see equations (20) and (21)).

2. In steady state, if the dynamical system is stock-solving, that is, equilibrium stocks may each be expressed as a function of yields, then a multispecies yield-effort function may be derived.

3. Even if a multispacies yield-effort function can be derived, it is likely to be highly nonlinear as a result of nonlinearities in the growth functions and components of the production function (see equation (26)). The derived yield-effort function may not be amenable to estimation, and economists may have to resort to specifying a presumed yield-effort function and employ duality theory to estimate parameters of interest (see equation (28)).

4. As in the single species bioeconomic model discussed in the first section of this paper, a bioeconomic optimum for the multispecies system will depend on. unit prices, costs, and the discount rate as well as parameters of the production and growth functions. Economists have yet to solve and explore the properties of a multispecies system such as that described by equations (38)-(42). Thus, rules for managing such systems are somewhat ad hoc and defy "crisp summary" (see May et al. 1979).

In light of the theoretical and empirical difficulties encountered in deriving and estimating a yield-effort function which is 'based on a fully understood multispecies bioeconomic model, it may be best to proceed in the interim in estimating presumed yield-effort functions. Such empir,ical work can shed light on parameters of policy importance, such as the aforementioned returns to scale, and substitution and transformation elasticities.

EMPIRICAL MULTISPECIES ANALYSIS: PROMISE AND PROBLEMS

In theory, the multiple-output production function and the duality-based techniques for estimating production parameters in the multispecies fishery would seem a perfect fit. Parameter estimates would provide valuable information when designing fishery management policies. For instance, suppose a translog form was presumed for our yield-effort function such that:

$$\begin{aligned}\ell n[H(\cdot)+1] = {} & \alpha_0 + \alpha_1 \ell n E_1 + \alpha_2 \ell n E_2 + \beta_1 \ell n Y_1 + \beta_2 \ell n Y_2 + \beta_3 \ell n Y_3 \\ & + \ell n E_1 \; (1/2\alpha_{1,1} \ell n E_1 + \alpha_{1,2} \ell n E_2) + 1/2\; \alpha_{2,2} (\ell n E_2)^2 \\ & + \ell n Y_1 \; (1/2\; \beta_{1,1} \ell n Y_1 + \beta_{1,2} \ell n Y_2 + \beta_{1,3} \ell n Y_3) \\ & + \ell n Y_2 \; (1/2\; \beta_{2,2} \ell n Y_2 + \beta_{2,3} \ell n Y_3) + 1/2\; \beta_{3,3} (\ell n Y_3)^2 \\ & + \ell n E_1 \; (\gamma_{1,1} \ell n Y_1 + \gamma_{1,2} \ell n Y_2 + \gamma_{1,3} \ell n Y_3) \\ & + \ell n E_2 (\gamma_{2,1} \ell n Y_1 + \gamma_{2,2} \ell n Y_2 + \gamma_{2,3} \ell n Y_3). \end{aligned} \tag{51}$$

The translog profit function takes the form:

$$\begin{aligned}\ell n[N(\cdot)+1] = {} & \alpha_0 + \alpha_1 \ell n c_1 + \alpha_2 \ell n c_2 + \beta_1 \ell n p_1 + \beta_2 \ell n p_2 \\ & + \beta_3 \ell n p_3 + \ell n c_1 \; (1/2\; \alpha_{1,1} \ell n c_1 + \alpha_{1,2} \ell n c_2) \\ & + 1/2\; \alpha_{2,2} (\ell n c_2)^2 + \ell n p_1 (1/2\; \beta_{1,1} \ell n p_1 + \beta_{1,2} \ell n p_2 \\ & + \beta_{1,3} \ell n p_3) + \ell n p_2 \; (1/2\; \beta_{2,2} \ell n p_2 + \beta_{2,3} \ell n p_3) \\ & + 1/2\; \beta_{3,3} (\ell n p_3)^2 + \ell n c_1 \; (\gamma_{1,1} \ell n p_1 + \gamma_{1,2} \ell n p_2 \\ & + \gamma_{1,3} \ell n p_3) + \ell n c_2 (\gamma_{2,1} \ell n p_1 + \gamma_{2,2} \ell n p_2 + \gamma_{2,3} \ell n p_3). \end{aligned} \tag{52}$$

Estimation of α_0, α_i, β_j, $\alpha_{i,i}$, $\gamma_{j,j}$, and $\gamma_{i,j}$ (i=1,2; j=1,2,3) may be undertaken with or without various equality, normalization, and symmetry restrictions. The resulting estimates would provide approximations of. efficiency, distribution, substitution, and transformation parameters, which in turn would allow resource managers to predict the response to various policies. For example, suppose one of our three species, say haddock, was thought to be overfished, while stocks of cod and flounder were deemed abundant. A landing tax on haddock would change the after-tax relative price, inducing shifts in the ratios of haddock/cod and haddock/flounder according to their elasticities of transformation. In another instance, suppose the rising cost of fuel had a differential impact on the cost of operating our two gear types (E_1, E_2). The elasticity of substitution would indicate the change in the ratio of gear/vessel types as a result of the differential change in effort costs.

In theory then, the parameter estimates of a multispecies yield-effort function would be of immense value in predicting industry response to changes in management policies or relative prices. To the author's knowledge, however, there have been no reports of successful attempts to apply duality-based techniques to multispecies production. There are at least three hurdles that must be successfully cleared prior to actual estimation; 1) defining appropriate input (effort) and output (yield) variables, 2) constructing measures for inputs and outputs as well as measures of 'their value (price) or cost, and 3) testing these measures for separability. Of these three hurdles or obstacles, the first two, definition and measurement, would seem to pose the greatest problems for applied research. In particular, the definition of fishing effort, its measurement, and the construction of appropriate cost data are particularly vexing. While the NMFS has historically collected data on landings and exvessel prices, the lack of a comprehensive data set on the cost of fishing precludes any straightforward attempt at the multispecies production problem. Within the NMFS the recent development of a financial simulator by Mueller and associates in the Northeast Regional Office may lead to the use of trip data and simulated cost data as a means of solving the problem of defining, measuring,' and assessing the cost of fishing effort.

In summary:

1) The multiple-output production function would seem a most appropriate paradigm for conceptualization and empirical research in multispecies fisheries.

2) Estimates of the parameters of a presumed yield-effort function or of its dual would greatly facilitate our ability to design effective management policies and predict the effects of economy-wide price changes on the vessels and stocks comprising a multispecies fishery.

3) The principal impediment to applying the multiple-output production function and the dual profit, revenue, or cost function would seem to lie in the definition and measurement of effort in the multispecies fishery. The joint use of trip-level data and simulated cost measures might provide a solution to this definition-measurement problem.

While the econometric problems of actual estimation are not to be taken lightly, the "policy promise" of the multiple-output approach would seem to hinge on the ability to define and measure the cost of multispecies effort.

REFERENCES

AGNELLO, R. J., and L. G. ANDERSON.

1977. Production relationships among interrelated fisheries. In Lee G. Anderson (editor), Economic impacts of extended jurisdiction. Ann Arbor Science, Inc., Ann Arbor, Mich.

CHRISTENSEN, L. R., D. W. JORGENSON, and L. J. LAU.

1973. Transcendental logarithmic production frontiers. Rev. Econ. Stat. 55:28-45.

CLARK, C. W.

1976. Mathematical bioeconomics: the optimal management of renewable resources. John Wiley & Sons, New York.

COBB, C., Andy P. H. DOUGLAS.

1928. A theory of production. Am. Econ. Rev. Suppl. 18:139-165.

CONRAD, J. M.

1982. Lectures on bioeconomics and the management of renewable resources. Cornell Univ.',' Ithaca, N. Y., Dep. Agric. Econ., staff Pap. 82-29.

DIEWERT, W. E.

1973. Functional forms for profit and transformation functions. J. Econ. Theory 6: 284-316.

DIEWERT, W. E.

1974. Applications of duality theory. In M. D. Intriligator and D. A. Kendrack-(editors). Frontiers of quantitative economics, volume 2. North-Holland Pub. Co., Amsterdam.

Fox, w. w.

1975. Fitting the generalized stock production model by least squares and equilibrium approximation. U. S. Natl. Mar. Fish. Serv., Fish. Bull. 73:23-37.

GORDON, H. S.

1954. Economic theory of a common-property resource: the fishery. J. Polit. Econ. 62:124-142.

HASENKAMP, G.

1976. Specification and estimation of multiple output production functions. In M. Beckmann and H. P. Kcnzi (editors), Lecture notes in Economics and Mathematical Systems. Springer-Verlag, New York.

MAY, R. M., J. R. BEDDINGTON, C. W. CLARK, S. J. HOLT, and R. M. LAWS.

1979. Management of multispecies fisheries. Science (Wash., D. C.) 205(4403):267-277.

SCHAEFER, M. B.

1957. Some considerations of population dynamics and economics in relation to the management of marine fisheries. J. Fish. Res. Board Can. 14:669-681.

SHEPARD, R. 'W.

1970. The theory of cost and production functions. 2nd ed. Princeton Univ. Press, Princeton, N. J.

SPENCE, A. M.

1974. Blue whales and applied control theory. In C. L. Zadeh et al. (editors) , Systems approaches for solving environmental problems. Mathematical Studies in the Social and Behavioral Sciences. Vandenhoeck and Ruprecat, Gottingen and Ziirch.

ON THE APPLICATION OF PRODUCTION THEORY TO BIOECONOMIC MODELING AND POLICY FORMATION: STATIC ANALYSIS OF COMMERCIAL CAPTURE FISHING

BY DALE SQUIRES

INTRODUCTION

Efficacious policy formation, management, and bioeconomic modeling of renewable resources such as commercial fisheries require a comprehensive understanding of the underlying production technology. Since commercial fisheries are often characterized by multiple species, cohorts, sizes, areas fished, multiple market categories, or sexes, the production technology should be specified within a multiple-output context as well. Knowledge of this technology is therefore a fundamental precondition of both static and dynamic, or capital,-theoretic, bioeconomic models and their consequent policy implications. However, this requirement has been largely neglected in both, the static and dynamic approaches to bioeconomic policy and model formulation. As a consequence, policy has often been misrepresented and, of equal importance, has been offered restrictive analytical results upon which to be developed.

The purpose of this paper is therefore to examine the importance of the production technology in a particular application of bioeconomic policy and modeling formulation--commercial capture fisheries. Special attention will be given to this technology in a multiple-output framework. Although in an ideal world policy and modeling should be firmly grounded within a dynamic or capital-theoretic context, this approach is generally intractable in practice. Instead, policy makers and managers tend to rely on some variation of the static, aggregate-output, Cordon-Schaefer model, while empirical bioeconomic analysts' usually limit their models to some type of highly aggregated static production function. Consequently, this paper will consider the specification of the production technology and its policy implications only within a static context, but with explicit consideration of the multiple-output problem and joint production. Although not directly discussed, implications for the production technologies of dynamic approaches will also be clear. Further, many of the general results may be easily extended to the production technologies of other types of renewable resources, such as forestry, water, soil,- and fish culture, and even expanded to the technologies of nonrenewable or exhaustible resource extraction.

This paper proceeds as follows. First, the general history of production theory applications to static commercial capture fisheries is presented. This discussion is generally oriented toward the single-output case. Some of the requisite restrictions or maintained hypotheses for statistical and mathematical tractability and limitations to these earlier, often pioneering studies will be surveyed in the process. Second, the general principles of the theory of the firm necessary for proper modeling are considered in the context of commercial capture fisheries. Third, the concept of duality theory is succinctly summarized, including Hotelling's Lemma. Fourth, attention is then turned to the multiple-product case. Within this context, consideration is first given to the general representation. of a production correspondence or transformation frontier.. Some of the characteristics of technology peculiar to multiple-output production receive particular emphasis. In this regard, the problems of joint production and separability and aggregation to form quantity and price indices are noted. Fifth, the choice of primal or dual representations of technology is considered. In this process, the choice of behavioral hypothesis and simultaneity bias are given close attention. Sixth, with the general 'historical and theoretical background established, the most general dual representation of technology, the restricted multiproduct profit function, is examined. A general flexible functional form is also considered within this context, and the principle results of this type of analysis are summarized. The seventh section of the paper then considers a particular specification of the restricted multiproduct profit function, the revenue function. The final section concludes with a brief review of bioeconomic models devoted to analyzing multiproduct production technologies and some of the required maintained hypotheses.

HISTORICAL REVIEW: ECONOMIC EXTENSIONS OF BIOLOGICAL MODELS

The first economic studies of static fishery production technologies were strictly based on biological foundations. They developed as economists extended biological models to incorporate issues of economic concern. Population dynamics formed an integral component of these pioneering models. These static extensions developed out of the seminal work of Gerhardsen (1952) and Gordon (1954)[1]. In these early studies, an aggregate, industry-wide production function was specified. A composite or aggregate specification was given both to the catch and to the non-biological factor input, fishing effort.

Construction of the composite input, standardized aggregate or fleet fishing effort, received considerable attention. In particular, a two-step procedure was followed. The first step related the rate of harvest to homogeneous or standardized fleet effort and the steady-state equilibrium level of the resource stock, and the second step related standardized fleet fishing effort to the economic inputs or costs.

The second step was one of the primary contributions by economists in these early studies, and therefore requires more detailed examination. All

[1]The seminal work of Scott (1955) provides the foundation for dynamic approaches to fishery modeling, including optimal control models.

studies standardized nominal effort (usually nominal fishing time, although sometimes nominal number of vessels) of specific gear types and/or vessel size-classes of concern through multiplication by fishing power. Fishing power itself was standardized with reference to the specific individual category. In this way, each unit of homogeneous individual category effort extracts a uniform proportion of the stock. The earlier studies determined individual category fishing power coefficients by comparing catch per unit effort of each gear type and/or vessel size-class when all were fishing at the same time or place. Later studies made fishing power an explicit function of the economic inputs or costs. The second approach allowed examination of the relationship between economic inputs, such as input substitution, or their individual effects. Homogeneous aggregate effort was then typically obtained by summing or taking the product of individual standardized effort over the fleet, depending on the underlying function. (See Kirkley and Strand (1981) and Huppert (1975) for further details.) Standardization was sometimes achieved with firm-level,data (Huppert 1975, Griffin 1977) and sometimes by aggregate data (Taylor 1980).

These models can be specified as some variant of

$$Y^* = f(E^*, X^*), \tag{1}$$

where Y^* equals optimum catch or yield in tons, E^* denotes the steady-state level of standardized fishing effort, usually adjusted for fishing power, and X^* denotes the steady-state equilibrium level of the stock.

RESTRICTIONS FOR TRACTABILITY

Biological and economic restrictions were imposed on these models to obtain mathematical and statistical tractability. The most important maintained biological hypothesis required the models to be static, since only steady-state equilibrium levels of catch, effort, and stock were considered. As a consequence, consideration was not given to the optimal approach paths or trajectories of the control (e.g., harvesting rate) and state (e.g., resource stock) (and costate) variables, to nonsteady-state equilibrium, or to nonequilibrium solutions. The growth functions specified were usually restricted to simple forms, such as the well-known logistic, and the models employed were generally highly restricted, such as the Schaefer Model.

Aggregate or composite output and input indices were specified to incorporate population dynamics and to allow analytical solutions to these models. However, attention was not given to the conditions of input and output separability and aggregation, or 'to the proper formation of price or quantity indices; i.e., to the conditions under which aggregate indices are properly formed. These conditions of aggregation and separability include multistage optimization processes, which when correctly specified, can include standardized fishing effort. Instead, the components of effort were implicitly (and probably unwittingly) assumed to follow the conditions for Leontief or Hicks aggregation or separability. The related implicit problem of simultaneity bias (through endogenous regressors) was neglected as well.

Similarly, in fisheries characterized by multiple species, cohorts, sexes, sizes, market categories, or areas fished, two basic approaches have been adopted. usually, a composite output index has been specified, again without properly considering the conditions for separability and aggregation. As before, the components of the composite output index were implicitly assumed to follow the conditions for Leontief or Hicks aggregation, or to satisfy homothetic separability requirements. By itself, an aggregate product index is implied by output separability and homotheticity in all outputs. However, more often encountered are aggregate indices for both outputs and inputs, thereby implying input-output separability, which in turn generally implies, jointness in inputs. Alternatively, production nonjoint in inputs has been specified, so that separate yield functions are utilized for species, sexes, cohorts, sizes, market categories, or areas fished. In this case, estimation procedures have not necessarily regarded a systems-wide approach, nor tested for nonjointness in inputs.

All production functions specified have been average or median (if in double log form such as the log-linear form of the Cobb Douglas) rather than frontier, and the model has been formulated as aggregate, industry-wide functions without regard to the bias inherent in aggregation from micro- to macrorelations.

MODELS PREDICATED ON THE THEORY OF THE FIRM

A third type of static fishery production modeling has emerged[2] Instead of trying to adapt the biological models to economics, the traditional economic theory of nonbiological, natural resource-based production has been adopted as the conceptual framework. The neoclassical theory of the firm therefore becomes the theoretical basis upon which a production study is predicated. This approach offers several potential advantages, including disaggregation of the composite input index, fishing effort, disaggregation of the composite product index if a fishery considered is characterized by multiple species or

[2]This section has borrowed heavily from Kirkley (1982), Kirkley and Strand (1981), Agnello and Anderson (1979), and Hussen and Sutinen (1979).

other forms of multiple outputs, detailed consideration of substitution and transformation relationships among various input and output combinations, analysis of joint production, utilization of more flexible functional forms, and greater consistency achieved with the neoclassical theory of the firm.

in short, by placing severely restrictive assumptions on the biological aspects of fisheries production modeling and by (usually) maintaining some type of economic behavioral hypothesis, hypotheses formerly maintained in the first two modeling approaches can be relaxed. In turn, the relaxation of these maintained economic hypotheses allows a fuller, more comprehensive treatment of static fisheries production from an economic framework. In particular, the focus has shifted from examining expected output given factor inputs and resource stock, to optimum allocation and economic efficiency criteria (Kirkley and Strand 1981). Finally, no inherent constraint exists by which the biomass equation and production function cannot separately be estimated and then combined to find equilibrium and optimal solutions (Henderson and Tugwell 1979).

To date, most of the studies predicated on the neoclassical theory of the firm focus on single-species fisheries without cohort, size, market category, area fished, or sex considerations. These studies also concentrate on the components of fishing effort using cross section data, although cross section and time series data are sometimes pooled. However, inadequate attention is sometimes given to the proper conditions for pooling. The unit of analysis is frequently at the vessel or firm level rather than industry-wide and aggregate. Technological externalities, however, such as crowding or stock effects, have received little attention, although Huang and Lee (1976) are a notable exception. Furthermore, when the analysis has been at the aggregate rather than the firm level, the proper conditions for aggregation from the micro- to macrolevels have not yet received proper attention. With only a few exceptions (Hannesson undated; Hannesson et al. 1978), the production functions specified have been average rather than frontier functions. In addition, the functions are usually primal specifications, or if in value terms, not predicated on the economic principles of duality (discussed below).

GENERAL PRINCIPLES

The general primal form of the static production function with a single or aggregate product and disaggregated inputs may be specified in general form as

$$Yt = f(Kt,Gt,HPt,Lt,Tt,Xt,St,At,Ot) \tag{2}$$

where[3]

Yt = total catch or yield in tons at time t,

Kt = vessel size at time t, usually expressed in GRT,

Gt = gear type at time t,

Hpt = engine horsepower at time t,

Lt = crew size (including captain at time t,

Tt = fishing time at time t, including steaming time,

Xt = an index of stock abundance at time t,

St = seasonal factors at time t,

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[3]In the balance of the paper, the time subscripts will not be written, but except at steady-state binomic equilibriums, they should be understood to be implicitly there.

At = area fished at time t, and

Ot = other factors at time t, including home port, vessel age, fishing skill or management, technical change, and vessel congestion and stock externalities.

The observation can be either aggregate or at the firm or vessel level. These inputs can be specified in either stocks or flows, but the latter is the correction specification; otherwise, biases will occur. To date, the models have all been specified as long-run in the nonbiological inputs. Gear switching has received little attention as well. At least one study has proposed normalizing output (catch in physical or value terms) by days at sea.[4] Dummy variables have also been used to account for multiple gear use. However, most studies specify different gears as part of separate production processes.

The typical functional form may be specified for such models as

$$Yt = AKt^{B1}Lt^{B2}Xt^{B3}e^{u}, \qquad (3)$$

which is the familiar Cobb-Douglas case. It is usually estimated by ordinary least squares (often without regard to serial correlation) in log-linear form:

$$\ln Yt = \ln A + B_1\ln Kt + B_2\ln Lt + B_3\ln Xt \ t \ u. \qquad (4)$$

Other functional forms utilized include the linear, CES, transcendental, and the homothetic function specified by Zellner and Revankar (1969). The limitations to most of these functional forms are well known and are not repeated here.

The disaggregation of nominal fishing effort has allowed examination of the substitution relationships between inputs and the individual effect of each input on the composite output. However, except for the study by Huang and Lee (1972), the proper conditions necessary for aggregation of many inputs

[4]This normalization has also been proposed as a means by which. to correct for the different times spent fishing by vessels.

into a small number of aggregate input indexes, that is the conditions necessary for weak homothetic input separability or multistage optimization, have been disregarded. The related issue of proper usage of input price and quantity indexes for measurement has also been neglected. Further, the substitution relationships have a priori been severely restricted, usually to a constant elasticity of substitution, most often equal to one.

LIMITATIONS

Any economic model of a fishery must conceptually incorporate some type of implicit or explicit model of population dynamics. Generally, a population growth function is not specified and estimated to obtain a measure of static steady-state equilibrium in models predicated on the theory of the firm. Instead, an implicit assumption often adopted specifies resource stock as a factor input which is constant or purely depletable. In this case, there may be a contradiction between constant resource stock and the long-run capital stock of vessel and engine. In addition, when stock size is specified as a factor input, harvests are not necessarily inherently constrained to some maximum possible level of catch, and it impossible to obtain diminishing returns without consideration of declining stock size. Further, an implicit assumption is made that the production functions are single-valued for any single output; that is, one level of fishing effort is associated with one catch level for each population. However, several levels of effort can all result in approximately the same level of catch. This can lead to nonconvexities. In addition, the origin property of well-behaved production functions may not be met; a strictly positive level of all inputs may be associated with a zero output level.

THE RESOURCE STOCK

Most studies specify the resource stock as a factor input. This approach implicitly assumes that the resource stock is a choice variable under direct control of the economic agent. However, because of the biological and social processes involved, at least in most capture fisheries, this is usually not the case. This specification may more accurately apply to aquaculture and mariculture.

Various representations of the resource stock as a factor of production have been adopted. On occasion, a measure of stock size has not been included, which may lead to omitted variable bias.

proxy variables have been the most frequent representations of the resource stock. Catch per unit effort (CPUE) or environmental surrogates for the resource stock are the usual proxy variable specifications. However, if CPUE is adopted, then biased and inconsistent estimates will arise due to the simultaneity problem. Further, industrial changes may make the effort variable subject to significant error over time, leading to biases from measurement error.

A common approach adopted in bioeconomic modeling uses environmental surrogates as the true variable with just a measurement error. With this specification, biased and inconsistent estimates will also occur, although the bias and inconsistency will be smaller than omitting the proxy variable. From a mean square error criterion, however, better estimates of the other coefficients may be obtained by omitting a proxy variable representation of biological abundance, under certain conditions. In addition, sometimes the proxy variable does not fall into the pure errors in variables category. Then the omitted variable bias without the proxy variable can be less than bias introduced by including the proxy variable, depending on the particular conditions of the nonpure errors in variable case. An example of a nonpure error in variable situation occurs if the proxy variable is a linear function of the unobservable variable with intercept and slope parameters. In general, therefore, except in cases where the proxy variable for the resource stock can be considered as a proxy variable with just errors in measurement, it does not strictly follow that using even a poor proxy variable is better than using none at all.

Additional problems may occur with this type of proxy variable approach. The most common type of environmental surrogate employed, biological abundance indices, may not account for seasonality. This approach; leads to additional specification errors, unless an annual or other highly aggregated model is specified, covariance analysis used, or the indices are partitioned out on a seasonal basis (Kirkley 1982). In addition, these variables are not observable until after the fact, they are not always subject to statistical validation, and sampling errors are also likely. The prior effects of management policies on the stock have also not been explicitly considered in this approach, although the approach by Kirkley (1982) implicitly incorporates this effect. Stock size or resource abundance is also a composite and narrowly defined variable.

Dummy variables represent another type of proxy variable for the resource stock which has been employed (e.g. Comitini 1978). In this approach, dummy variables account for fluctuations in harvests due to noneconomic phenomena, but especially due to variation in the resource stock over time and sometimes area. When dummy variables are used as proxy variables in this manner, the resulting biases may either increase or decrease, depending on the assumptions made about the behavior of the other regressors and the unobserved resource stock.

In summary, when a n&stochastic proxy variable for resource stock as a factor input is utilized, reductions in bias and inconsistency may occur, depending on the assumptions made about the behavior of the unobserved variable and the other regressors, as well as the type of relationship between the proxy and unobserved variables. Furthermore, from a mean square error criterion, employment of a proxy variable for resource stock as a factor of production may not always be superior to omitting the proxy variable entirely. Resolution of this matter, given the specification, is thus essentially an empirical matter.

Estimation of the parameters or production models utilizing the resource stock as a factor input may have at least two additional econometric problems, ones which will be only briefly noted. First, even if a true or exact representation for the resource stock could be found and employed (rather than a proxy variable), the variable may still contain errors of measurement. In this case,, least squares estimates of the parameters in these models will be biased and inconsistent because the classical assumption about the independency of the stochastic term and the regressors is violated. Second, the resource stock may be a stochastic variable rather than fixed.

The resource stock can also be specified as a technological constraint rather than a factor input.[5] Ii the resource stock is conceptualized as a technological constraint, then, "For each given level of population, a larger

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[5]See for example, Gordon (1954:136) and Kirkley (1982).

fishing effort will result in larger landings. Each population contour is, then, a production function for a given population level.[6] That is, a change in resource availability leads to a change in the production function or production correspondence, which in turn should affect the constant term.

CAPITAL

The measurement and specification of capital has always presented a problem in economics. Varian (1978) states that the ideal measure would be of capital services, since output is measured as units of the good per unit of time. Therefore, capital should be measured as machine hours. Capital services also recognizes that the same number of machines may be used more or less intensively (capital utilization), and that different vintages of 'machines may provide different levels of capital services due to technological differences. Capital services further recognizes that net capital is an incorrect measure, since capital reflects the age of the equipment (the machine that gives identical capital services over its lifetime should have the same value each year whatever the net worth of the machine). Therefore,' gross capital (and thus capital services) is more satisfactory, although it ideally should be amended to take account of not the decline in value, but the decline in efficiency of a piece of equipment as it ages. If a net capital concept is used, a bias is introduced, although probably not a large one, unless the age distribution of the capital stock is extraordinarily irregular.

One measure of capital services, in a primal time series specification as a long-run variable and in a dual specification as a fixed factor, is

[6] Cordon (1954).

ton-days fished.[7] Ton-horsepower-days fished provides another, related measure of capital services. Comitini (1978) has successfully used the rate of depreciation as well. Still another approach, by Comitini and Huang (1967), has measured capital value and then deflated by a price index to provide a measure of the level of capital stock. This level is then adjusted by a utilization rate, which provides a capital services flow. Dummy variables for individual vessels without a specific capital variable have also been used. Utilization of a capital services price has not yet been applied. Several other approaches have also been advocated in the economics literature.

The most important consideration, which is not always considered by fisheries production studies, entails transformation and usage of capital stock data into flows since production functions represent the relationship between input and output flows. Only if the flow of capital services is proportional to stocks can stock data be employed without biasing the results. Finally, if cross-section estimates are made, an implicit assumption is adopted that all of the firms are in long-run equilibrium in their capital - stock (in some instances, this can be empirically tested), while time series specifications implicitly assume firms are not in long-run equilibrium in capital stock.

MANAGEMENT AND FISHING SKILL

Management has always presented a problem in production studies. In fisheries, management and fishing skill are sometimes termed the good captain

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7Personal communication, Jim Kirkley, NMFS, Northeast Fisheries Center, Woods Hole, Mass.

hypothesis. Although management's importance has probably decreased slightly with the introduction of electronic equipment, it is probably still of great importance. This point has been particularly stressed by Carlson (1973), Rothschild (1972), Comitini and Huang (1967), MacSween (1973), Wilson (1982), and Buchanan (1978).

Although management's importance is generally recognized in the general production literature, efficacious means by which to incorporate it into a production relationship are difficult. For example, the most common approach has generally been to omit management altogether. However, as Grilliches (1957) has shown, the consequent omitted variable bias depends on the correlation between the management variable and all of the included variables.

Mundlak (1961) and Hoch (1962), in estimating a Cobb-Douglas production function, assume that managerial skills cause neutral shifts in the production function with no change in factor elasticities. The assumption of neutrality is weak, although computationally necessary. However, no reason exists to expect management to effect all factors equally.

A number of additional methods have been proposed to eliminate the specification bias resulting from the omission of management. A few of these approaches will be examined here to provide an indication of the problem and the most accessible possible approaches. Proxy variables have been the most widely adopted solution. As discussed above, covariance analysis is one approach. Comitini and Huang (1967) utilized this approach in fisheries to account for disembodied managerial differences.

Cardinal proxy variables for management have also been utilized in the general economics literature. Carlson (1973) suggests. that years of schooling or years of captain experience may be appropriate for fisheries. Carlson (1973) also suggests that the best captains would gravitate to the best vessels, because they would be able to buy the more productive vessels, or be hired away from the poorer vessels.' To the extent that the most productive vessels are the newest, vessel age would represent a proxy variable for management, as well as for different capital vintages.

An alternative to the use of a proxy variable for management is the assumption that between vessels, within time periods, residual variation represents the influence of management. However, this approach is limited, since residuals represent all excluded factors, not only management. Residuals also reflect measurement errors as well as stochastic influences; A random coefficients model is an alternative approach. If the coefficients of physical inputs depend on characteristics related to differences in management quality, and if coefficients vary across firms, then exact measures of all the sources of variability may not exist, all sources of variability may not be known or clearly understood, and random shocks may change the coefficient across firms and over time for any given firm. Thus, a random coefficients model is appropriate in this case. The literature is extensive in this area for a fairly intractable problem.

FUNCTIONAL FORMS

Restrictive functional forms have generally been imposed. These forms embody the restrictive maintained hypotheses on technology of homotheticity, homogeneity, separability, and constant elasticities of substitution. In the Cobb-Douglas case, elasticities of substitution are a priori restricted to one. The individual input indices have usually been a priori specified as strongly separable, since the Cobb-Douglas or CES functional forms have been the most widely employed. Consequently, if the aggregate input index fishing effort is employed, the marginal rates of technical substitution within effort are assumed to be invariant to changes in stock size (as a factor input) or other inputs. The regularity conditions of quasi-concavity or convexity and monotonicity necessary for a well-behaved production function are usually not tested for, even by ex-post parametric means.

TECHNICAL CHANGE

Technical change has received some attention when cross-section data have been pooled with time series. However, the form of the technical change has been a priori restricted to be factor augmenting at constant exogenous rates so that a linear time trend can be utilized (usually after a logarithmic transformationof technical change occurring at an exponential rate). In addition, technical change has been even further restricted to be Hicks neutral (so that the production technology is implicitly assumed homothetic if Hicks neutrality holds), and no attempts have been made to determine whether the rate is changing over time (by employing a flexible functional form for estimation).

Scale- and scope-augmenting technical change and economies of scale and scope have received little or no attention. As Wilson (1982) notes, uneven concentration and changing distribution of fish over time and area create circumstances in which the efficiency of vessels varies considerably. In. addition, in a fishery characterized by multiple outputs (e.g., species, sexes, sizes, cohorts, market categories, etc.), the changing distribution includes changes in both the composition and levels of these components. Weather is an additional related yet distinct source of variation. As a Consequence, an excess capacity problem analogous to peak loads ‘in electric utilities exists. Therefore, due to the variability of the resource stock and weather and the resulting uncertainty facing harvesters, the optimum scale or scope economies may be larger than those found in a stable production environment. What may appear to be an inefficient scale or scope of production at one time period may not be at a subsequent time. Ostensibly, inefficient production may also be associated with learning, especially in what is essentially a hunting production process where the importance of management, experience, and skill are enhanced. An inducement toward scale-augmenting technical change may also exist as a consequence; Scale-augmenting technical change may also be obfuscated by fluctuating resource stocks and economies of scale. In a multiproduct industry, characterized by substantial uncertainty, technical change may also be biased towards increased diversification of product mix and area harvested and flexibility of vessel design favorable to gear changes. Scope-augmenting technical change may be obscured in a manner similar to scale-augmenting technical change.

DUALITY THEORY IN A NUTSHELL

Before examining static single-species production from the perspective of duality, a brief review of duality theory will be provided.[8] The concept of duality essentially states that (for a short-run case), technology can be equivalently and alternatively represented by: 1) the restricted production possibilities set, T; 2) the restricted production function, $f: R_+^N \times R_+^K \longrightarrow R_+$, which can be defined as

$$Y = F(X;Z), \qquad (5)$$

[8]Varian (1978) provides an introduction, and Lau (1978),, McFadden (1978), Fuss et al. (1978), Laitenen (1980), and Nadiri (1982) provide more advanced treatments.

where X is an NX1 vector of variable inputs and Z is a KX1 vector of fixed factor flows; and 3) the restricted profit function, defined as

$$\pi(P, R, Z) = \max_{Y,X} \left\{ PY - R'X = (Y, X; Z) \in T \right\}, \tag{6}$$

where P is a fixed product price, R is an NX1 vector of variable input prices, and $(P, R) >> (O, O_N)$.

HOTELLING'S LEMMA

.A number of duality theorems exist. The most important one for empirical work is Hotelling's Lemma. Consider a restricted profit function (P,R;Z). Then for (fixed) Z, Hotelling's Lemma provides the optimal variable product supply and variable factor demand correspondences at the profit-maximizing vector of variable product and variable factor prices, (P*,R*):

$$\partial\pi \frac{(P^*,R^*;Z)}{\partial P} = Y^*(P^*,R^*;Z), \tag{7}$$

$$\partial\pi \frac{(P^*,R^*;Z)}{Rj} = -X^*j(P^*,R^*;Z) \quad j = 1,...,N, \tag{8}$$

$$\partial\pi \frac{(P^*,R^*;Z)}{\partial Zk} = \frac{\partial F(Y^*,X^*;Z)}{\partial Zk}, \quad k = 1,...,k, \tag{9}$$

where Y^* is the variable product supply function and X^*j is the jth variable factor demand function. Hotelling's Lemma states that the variable product supply function is provided by the first partial derivative of the restricted profit function with respect to the output price, and that the negative of the jth variable factor demand function is provided by the first partial derivative of the restricted profit function with respect to the jth variable factor price.

To date, duality theory has not been applied in the single species case. The most probable explanation lies with the difficulty in obtaining reliable input prices, especially at the vessel level, in defining inputs and their prices in a fishery (witness the recent debate over the opportunity cost of labor) and with the relatively recent introduction of duality theory.

GENERAL PRINCIPLES OF MULTIPRODUCT PRODUCTION TECHNOLOGIES

TRANSFORMATION FRONTIERS

Multiple-species fisheries have received some attention with a (static) primal specification. However, before examining this topic in greater depth, first consider some additional notation and specifications.

For the multiproduct firm, the production correspondence or transformation frontier provides one representation of its production technology. This set of efficient input-output combinations may be described symmetrically as the. set of (Y,V;Z) which satisfies the equation $F(Y,V;Z) = 0$, where F is the symmetric transformation frontier and Y is now an MX1 Vector of outputs. Alternatively, one numeraire commodity, either an output or n&producible input, may be singled out as the left-hand variable to provide an unsymmetric transformation frontier for efficient input-output combinations.

If an output is singled out as the numeraire commodity, say Y_{m+1}, then the transformation frontier may be defined as the maximum amount of Y_{m+1} which can be produced given the amount of the other commodities, $Y' = (Y_1,...,Y_m)'$ and $v' = (v_1,...,v_n)'$. The unsymmetric transformation frontier, $Y_{m+1} = F(Y,V)$, may not be well-defined for any nonnegative vectors of other outputs and inputs. If the components of other outputs Y are chosen to be larger while the components of v remain small, then it may be possible to produce any nonnegative amount of Y_{m+1}. In this case, $F(Y,V) = -\infty$. The unsymmetric transformation frontier which corresponds to the production possibilities set T may therefore be defined as

$$
(Y,V) \quad \begin{cases} \max_{Ym+1} \{Ym+1: \; (Y,Ym+1,V) e\; T\} \\ \qquad \text{if there exists } Ym+1 \text{ such that } (Y,Ym+1,V) \; e \; T, \\ -OO, \text{ otherwise} \end{cases} \qquad (10)
$$

M N

for all YeR+ and VeR+.

The regularity conditions generally assumed for a well-behaved production correspondence are given by Diewert (1973), Fuss et al. (1978), Jacobson (1970), Lau (1978).

Two basic approaches have been adopted to date in primal examinations of multiple-species fisheries. The most common approach aggregates all species, sexes, and cohorts into a composite output index without regard to the conditions necessary for their aggregation. As a consequence, input-output separability--and therefore probably joint production in inputs--has been specified as

$$Ym+l = F(Y,F(V) 1. \qquad (11)$$

or alternatively,

$$g(Y,Ym+1) = f(V), \qquad (12)$$

where f(.) and g(.) are input and output aggregator functions, respectively. Concavity of F then requires f(.) to be convex and g(.) to be concave.

INPOT-OUTPUT SEPARABILITY

A specification of this nature is very restrictive. First, jointness in all inputs or output dependence implies that all inputs are required to produce all outputs. Alternatively, if block jointness in some inputs or block output dependence exists, then for each set or sets of inputs and outputs, all of the inputs (in each set) are required to produce all of the outputs (in that set). Second, input-output separability implies that the set of all isoquants is fixed and is independent of output composition.[9] Consequently, if a change in the species, age, or sex composition of ex-vessel demand occurs, no corresponding change occurs in the relative proportions of the optimal (variable) input combination. In addition, the marginal rates of technical substitution between pairs of variable inputs are independent of the output composition but not the levels, unless almost homotheticity in inputs does not hold. The same types of implications of input-output separability hold in output space. It is also not possible to obtain the separate effects of individual inputs. Instead, only the effects of the aggregate input, fishing effort, on aggregate output can be considered.

The composite output index in the multiple-species case has been specified in both physical terms as tons harvested and in value terms as total revenue. One rationale given for the latter specification is that in a multiple-species fishery, maximization of gross returns is more commonly found than maximization of total pounds harvested and landed, i.e., fishermen are more concerned with earnings than weight itself. A second rationale is that considerable differences may exist in the expected prices and expected catch rates among the various species harvested at any given time. In both of these cases, the aggregator function is thus a simple linear function. In the latter case, prices form weights, and an implicit assumption is made that output price is invariant with respect to output. However, a simple weighted or unweighted linear aggregation assumes that commodities are identical, perfect substitutes, or zero substitutes.

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[9] Other possibilities include homothetic output separability, leading to a single aggregate output, and homothetic input separability, leading to a single aggregate input.

AGGREGATION

More general conditions exist under which the arguments of a function may be aggregated. One possibility entails use of the Hicks or Leontief conditions for aggregation. In the Hicks' approach, variable product (or variable factor) prices for the commodities of concern are required to vary proportionately, while the Leontief conditions require the product (or factor) quantities to vary proportionately. However, it may be desirable to have properties of aggregation that do not depend on the peculiar features of a particular price system for Hicks aggregation. Further, the fixed proportions technology for Leontief aggregation is a very stringent requirement from a theoretical perspective.

If the Hicks or Leontief aggregation theorems do not hold or their use is considered undesirable, an alternative procedure for aggregation of outputs (and inputs) leads to Solow's (1955, 1956) consistent,aggregates by use of the two-step aggregation process. Weak separability is necessary and sufficient for the existence of aggregates. Homotheticity is a necessary and sufficient condition for the validity of the two-step procedure. However, the further restriction of linear homogeneity of the aggregator functions is required to ensure that the product of the aggregate price and quantity indices equals total revenue (or total cost) of the components. Therefore, necessary and sufficient conditions for the existence of such consistent aggregates are weak separability and aggregator functions homogeneous of degree one. Following Lau's (1978) approach, this leads to his more restrictive definition of weak homothetic separability. Further, when only two groups are distinguished, separability alone is necessary and sufficient. Finally, as Fuss (1977) notes, if an aggregate index is created by this two-step optimization process, it forms an exogenous instrumental variable which is predetermined in the submodel- (in-addition, multicollinearity is reduced). In contrast, some indices not formed in a proper manner may lead to simultaneous equations bias, since they are assumed exogenous even though they may be more correctly specified as endogenous.

When total revenue has been used as a measure of harvest in a multiproduct fishery, then not only have the requirements for aggregation not generally been satisfied, but the proper conditions under which revenue functions provide information about the production technology have not been explicitly considered. However, a complete discussion of revenue functions is postponed until duality-based approaches are examined.

JOINTNESS IN INPUTS

The second basic approach to static production modeling of multiple-species fisheries has disaggregated the composite output index and a priori specified production that is nonjoint in inputs. Therefore, separate yield functions for different species (or sexes or cohorts) are specified. Although multiple-species fisheries may very well be nonjoint in inputs, this specification should be tested for and the possible economies of scope determined, if any, rather than retained as a maintained hypothesis--even if the only available tests are ex-post and parametric. Another, even more likely possibility is block jointness in inputs or block output independence when joint in inputs products exist for certain subsets of species harvested but not over the entire universe of possible species harvested in the multispecies fishery. For example, block jointness in inputs and economies of scope may exist among cod and haddock versus yellowtail and other flounders in the New England groundfishery. In any case, this is an empirical question--one which must be empirically determined.

MAINTAINED-HYPOTHESIS AND RESTRICTIONS

The functional forms specified to date in multiple-species studies have been restrictive. However, the advent of flexible functional forms allows examination of a large number of economic effects and allows fewer hypotheses to be maintained. In particular, the comparative statics effects at a point of output level, returns to scale (or size), distributive share, own-price elasticity, elasticity of substitution, and exogenous technical change can be quantified in terms of the production function and its first and second partial derivatives without imposing restrictions across these effects. Additional auxiliary topics can be considered as well.

Maintained hypotheses are also important in choice of functional form. These hypotheses are nested according to their degree of fundamentality. The most important of these restrictions on technology, which have been progressively relaxed with the flexible functional forms, are separability, substitution, homogenity, and homotheticity. These formerly maintained hypotheses can now be ex post facto parametrically tested for, and in the case of homogenity and homotheticity, are nested. To date, flexible functional forms have yet to be employed in static fisheries production studies.

A specification of technology is available which provides disaggregation of both the output and input indices, but which a priori imposes relatively few restrictions on technology and allows comparative statics effects at a point to be examined. The specification is the multiple-output, multiple-input production function, or one of its dual forms, with a flexible functional form. This particular transformation frontier or production correspondence allows many of the restrictions or hypotheses formerly maintained on technology to be empirically tested for, albeit parametrically and ex post facto.

However, very real limitations to this approach exist in addition to the usually maintained hypotheses of convexity monotonicity, continuity, and differentiability and in the dual specification, linear homogenity in. prices, and a symmetry property in price response.

CHOICE OF PRIMAL OR DUAL REPRESENTATIONS OF TECHNOLOGY

The choice of a primal or dual approach depends upon at least five factors: 1) the type, quantity, and quality of data available; 2) the type of results desired (e.g., marginal products rather than price elasticities); 3) the choice of exogenity partition (quantities or prices); 4) the choice of behavioral hypothesis; and 5) ease of econometric estimation. In the ideal world of concern here, selection of the behavioral hypothesis is most important, since different types of behavioral assumptions strongly affect the mathematical and statistical specification of the models, as well as their tractability.

BEHAVIORAL HYPOTHESES

Considerable debate still exists as to the proper behavioral assumptions to be specified for various fisheries. In principle, direct estimation of transformation or production frontiers or functions using data on output and input levels does not require behavioral hypotheses with respect to firms. However, in practice most studies have relied on optimization conditions such as maximization of catch or harvest landed. The econometric problems associated with simultaneous equation bias may be serious if firms are cost minimizers and/or profit maximizers. In general, unless some rather restrictive assumptions are made such as constant returns to scale, separability, and nonjointness in inputs, direct estimation of a production correspondence may be econometrically difficult. For these reasons, the use of duality between prices and quantities may be desirable.

COST MINIMIZATION

Dual specifications of technology require alternative behavioral assumptions and data. Cost minimization is the most widely employed dual approach, one which is most appropriate if outputs are exogenously determined. Although many multiproduct fisheries come under regulation, the degree is insufficient to imply exogenity of catch. If output is assumed constant, the scale or output effects of an input price change cannot be calculated from the estimated cost function. Further, if the firms are profit maximizers, then the inclusion of output levels as explanatory variables may lead to simultaneous equation bias of the estimation. The problem is compounded when multiproduct cost functions are estimated. In this case, the input share equations are dependent on each of the output variables unless homothetic separability is assumed. However, if firms are assumed to be profit maximizers, so that the cost function is considered as merely the first step in a two-step profit maximization process (cf. Theil 1980 or Laitenen 1980), revenue share equations are therefore included as a result of marginal cost pricing and iterative three stage least squares estimation applied, then perhaps the problem may be mitigated.

REVENUE MAXIMIZATION

Revenue maximization allows outputs to be endogenous. In this case, fishermen consider the expected prices and catch rates in directing effort towards species and grounds. This approach directly provides the basic structural relations underlying market responses, such as the net substitution or complementarity effects among output pairs, isolated from the expansion effects associated with input changes in response to product price variations. However, information is not provided concerning the relationship between inputs (which are assumed constant), and the costs of production are implicitly assumed to be of little or no concern. In addition, the estimation of the conditional or revenue-maximizing variable product supply equations associated with the revenue function implies simultaneity problems with respect to the input variables used as explanatory variables if the firms are cost minimizers.

PROFIT MAXIMIZATION

If expected species prices, expected catch rates, and harvesting costs all determine the output and input choices, then profit maximization is the desired behavioral assumption. Consequently, the profit function approach,' which requires joint estimation of both (variable) product supply and (variable) factor demand correspondences as functions of output and input prices, does not imply any problem of endogeneity of the explanatory variables if firms are price takers in the input and output markets. The profit function approach also provides the full comparative statics effects, which include the substitution and expansion effects, via the Hessian matrix of the profit function. In contrast to the cost or revenue functions, the substitution or complementarity effects isolated from the scale or expansion effects are not directly obtained, although a method exists by which to do so.

It is likely that in a choice among these primal and dual behavioral hypotheses and their consequent model specifications, the time period under consideration is of substantial importance--the longer the time period, the more appropriate profit maximization becomes. Richer and more complete behavioral hypotheses would consider risk and uncertainty through expected utility maximization. Since neglect of risk averse behavior leads to biased estimates, further attention may be required in this area. Finally, note that if profit rather than expected profit is specified, simultaneity bias is likely.

THE MULTIPRODUCT RESTRICTED PROFIT FUNCTION

Consider next the most general case, that of expected profit maximization with at least one input or output held fixed, with risk neutral behavior. Then dual to the unsymmetric restricted transformation frontier is an expected restricted normalized profit function:

$$E(\pi) = \pi(E(P),\ R;\ Z), \tag{13}$$

where P is an MXl vector of variable product prices normalized by the (MXl)th output price, R is an NXl vector of variable factor prices also normalized by the (NX1)th output price, and Z is a KX1 vector of fixed product and factor flows. All prices are strictly greater than zero.

A profit function generally requires decreasing returns to scale. If constant or increasing returns to scale exist, then profit is usually constrained to zero. Pure competition is implicitly assumed by this approach. At the harvesting level in most fisheries, the assumption of pure competition is generally acceptable due to the generally large number of firms and little concentration of production by vessel owners or processors. The static normalized restricted profit function and its derived correspondences also assume that firms are price takers, i.e., that prices are taken as given and therefore are strictly exogenous to the firm, and that quantities of fixed products and factors are also given or strictly exogenous. If these variables are in fact not strictly exogenous to the firm, but rather are endogenous or simultaneously determined, their inclusion would lead to simultaneity bias unless iterative three stage least squares estimation is applied.

LABOR

If labor is considered as a variable input, then either the opportunity cost of labor can be included or iterative three stage least squares applied so that the returns to labor are simultaneously determined with profits. Alternatively, labor may not be a choice variable in the short run once a lay system is established. In this case, it may be more appropriate to specify labor as a fixed factor. This specification may also be appropriate if the stock of capital is considered fixed and crew size considered to be in fixed proportion to the capital stock. A specification test for exogenity may be appropriate for labor in this case. Risk considerations and biases may not be necessary if a lay system is utilized, since risk is passed on to the crew, thereby implying risk neutrality.

FLEXIBLE FUNCTIONAL FORMS: THE GENERALIZED QUADRATIC

The expected normalized restricted profit function specified in the generalized quadratic flexible functional form becomes[10]

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[10]The generalized quadratic can be either a true or exact representation of technology in its own right, or a second-order approximation to an unknown underlying functional form. There are econometric advantages to each approach. Also, expectation operators are not explicitly written, and all future prices are assumed certain.

$$\Psi(\pi) = \alpha_0 + \sum_{i\varepsilon m} \beta_i\phi_i(p_i) + \sum_{j\varepsilon n} \gamma_j\phi_j(r_j) + \sum_{k\varepsilon s} \delta_k\phi_k(z_k)$$
$$+ 1/2 \sum_{i\varepsilon m} \sum_{u\varepsilon m} \beta_{i,u}\phi_i(p_i)\phi_u(p_u) + 1/2 \sum_{j\varepsilon n} \sum_{v\varepsilon n} \gamma_{j,v}\phi_j(r_j)\phi v(r_v)$$
$$+ 1/2 \sum_{k\varepsilon s} \sum_{w\varepsilon s} \delta_{k,w}\phi_k(z_k)\phi_w(z_w) + \sum_{i\varepsilon n} \sum_{j\varepsilon n} \eta_{i,j}\phi_i(p_i)\phi_j(r_j)$$
$$+ \sum_{i\varepsilon n} \sum_{k\varepsilon s} \mu_{i,k}\phi_i(p_i)\phi_k(z_k) + \sum_{j\varepsilon n} \sum_{k\varepsilon s} \lambda_{j,k}\phi_j(r_j)\phi_k(z_k). \tag{14}$$

The generalized quadratic easily becomes one of the commonly employed flexible functional forms according to the metrics specified.[11] In addition, a number of restrictions are usually imposed on the expected normalized restricted profit function, including the maintained hypotheses of symmetry and linear homogeneity in all prices. Additional restrictions, some of which are nested, and all of which can be ex post facto parametrically tested for, include homogeneity in the fixed factors, almost homotheticity in outputs, almost homotheticity in inputs, almost homogeneity in the outputs, almost homogeneity in the variable inputs, almost homogeneity in the variable outputs, input separability, output separability, input-output separability, and jointness in inputs.

By applying Hotelling's Lemma to equation (14), planned variable product supply and planned variable factor demand equations are obtained:

$$S_i = \frac{\partial\Psi(\cdot)}{\partial\phi_i(p_i)} = \beta_i + \sum_{u\varepsilon m} \beta_{i,n}\phi_u\,(p_u) + \sum_{j\varepsilon n} \eta_{i,j}\phi_j(r_j)$$
$$+ \sum_{k\varepsilon s} \mu_{i,k}\phi_k(z_k)\ ,\ i = 1, \ldots, m. \tag{15}$$

$$S_j = \frac{\partial\Psi(\cdot)}{\partial\phi_j(r_j)} = \gamma_j + \sum_{v\varepsilon n} \gamma_{j,v}\phi_v\,(r_v) + \sum_{i\varepsilon m} \eta_{i,j}\phi_i(p_i)$$
$$+ \sum_{k\varepsilon s} \lambda_{j,k}\phi_k(z_k)\ ,\ j = 1, \ldots, n. \tag{16}$$

[11] In particular, the generalized Leontief, translog, quadratic, generalized quadratic mean of order P, and the generalized Box-Cox are all easily obtained and can be interpreted as Taylor's series approximations. Commonly used flexible functional forms which do not have interpretations as Taylor's series approximations include the generalized Cobb-Douglas and mean of order two. Some of these are self-dual forms.

COMPARATIVE STATICS EFFECTS AT A POINT

After the proper econometric specification and estimation, further differentiation of equations (15) and (16) provides the usual comparative statics effects of changes in variable product and variable input prices, and changes in the quantities of fixed product and factor flows. Through simple scaling or linear transformation, own and cross net price and quantity elasticities of product supply and input demand are obtained. If the technology is not input-output separable but is joint in inputs, then these net price elasticities include not only the usual substitution effects, but expansion effects as' well. For example, a change in an input price not only causes the change in input ratios which induces technical substitution among the inputs along the initial isoquant frontier, but also entails changes in all the outputs along the new expansion path associated with input prices, contributing to the additional variation in variable input demand. For this reason, without input-output separability or nonjointness in input, Allen partial and Hicksian elasticities of substitution and transformation cannot be derived by the usual method of resealing the net price elasticities by shares, unless the approach indicated by Lopez (1981) is applied.

PRINCIPLE RESULTS OBTAINED FROM RESTRICTED PROFIT FUNCTION

In summary, the principle results obtained are two basic kinds. First, through ex post facto parametric tests information is provided concerning the nature of technology such as input-output separability and jointness in inputs. Several implications follow. For example, if the technology is not joint in inputs, then the subsets of a multiproduct fishery can be considered separately in the short run when the resource stock is not assumed constant;

however, biological interdependencies must be considered. Information on multiproduct returns to size may also be useful to ensure efficient licensing. Alternatively, if multiproduct returns to size equal one, then economic rents are not available to pay for the services of the fixed factors and the long-run viability of the sector would be in question. If ray returns to size were found greater than one, expected profit-maximizing levels of output could not be found as the firm expanded to infinite levels of input use. Again, the viability of the sector would be in doubt. It is this condition of increasing ray returns to size that is a traditional rationale for government intervention to fix prices which would otherwise be driven below minimum average costs. If pooled cross sectional and time series data are used, insights into the nature of technical change can also be found. For example, technology can be found to be Kicks neutral or biased and its rate of time change estimated.

The second result of a multiproduct analysis are sets of price and quantity elasticities and an estimated restricted normalized profit function. The price elasticities are between 1) each pair of species indexes, or variable outputs; 2) each pair of variable inputs; 3) each variable input price and variable product supply; and 4) each variable product price and variable factor demand. These can all be evaluated at different levels of the fixed products and factors, e.g., for different stock sizes (if the latter is specified as a fixed factor of production). The quantity elasticities are between the fixed product and factor flows and variable product supply and variable factor demand, and between pairs of fixed factor and product flows. These types of results are one of the primary reasons for applying the 'principle of duality.

These elasticities can be used to assess the impact of changes in the prices of variable inputs, fuel, for example, on variable output prices, and the levels of fish stocks upon the level, direction, mix, and significance of fishing effort and harvest. The short-run effects of such management policies as landings taxes or harvest quotas can also be assessed. Depending- on the model specification, the (short-run) effects of expansion of unregulated variable inputs can also be examined.

The normalized restricted profit function can also be directly used to study the impact of various management policies on restricted profits, although without consideration of changes in the composition of species and variable inputs. Finally, through analysis of covariance, distributional impacts of management policies or price or quantity changes across fishing grounds, ports, and vessel size-classes might also be examined.

THE REVENUE FUNCTION

Since the available fisheries data are sufficiently detailed and available only on the output side, the revenue function requires further attention. Conceptually, the revenue function is a restricted profit function in which all inputs are exogenous , hut some outputs are endogenous. If all outputs are endogenous, this gives the long-run revenue function:

$$TR\ (P;Z) = P\ (P;Z). \tag{17}$$

If some outputs are exogenous, the restricted or short-run revenue function is

$$TR\ (P;Z^*) = P\ (P;Z^*), \tag{18}$$

where Z is now a vector of fixed factor flows and Z* is a vector of fixed factor and product flows.[12] output markets are assumed competitive.[13]

[12]The cost function is similarly the negative of the restricted profit function in which all outputs are exogenous, but some inputs are endogenous.

[13]See Diewert (1974) and Sakai (1974) for the regularity conditions and duality theorems.

PRINCIPLE RESULTS OBTAINED FROM REVENUE FUNCTION

The revenue function and the system of conditional variable product supply equations are econometrically estimated, and comparative statics effects of the revenue-maximizing firm obtained from these results. As discussed above, the effects of a variable product price change, the comparative statics effects, are only substitution or complementarity effects among pairs of variable products without expansion or scale effects due to changes in variable inputs resulting from the changes in variable product prices. That is, a change in relative variable product price ratios induces a movement along the product transformation curve. This change in the composition of variable outputs does not induce changes in the inputs through movement along the original isoquant or changes in the inputs through shifts in or out of the set of isoquants. If the technology is nonjoint in outputs, the requirements for each input are determined solely by the set of outputs; i.e. a set of separate factor requirement functions is obtained.

QUADRATIC SQUARE ROOTED FUNCTION FORM

Diewert (1974) presents a specification of a revenue function and its associated conditional variable product supply equations. In particular, a technology with one aggregate input (implying input separability) and multiple outputs is discussed. A revenue function and conditional product supply functions can be estimated with the self-dual flexible functional form given by the quadratic square root

$$S^2 = \sum_{i\varepsilon m} \sum_{u\varepsilon m} a_{i,j} P_i P_j X^2 , \; a_{ij} = a_{ji}, \tag{19}$$

where S is defined as revenue. The conditional product supply correspondences can be obtained by applying Hotelling's Lemma to the revenue function, and may be written as

$$S_{Y_i} = \sum_{i \in M} a_{ij} P_j X^2, \quad i = 1,\ldots,M. \qquad (20)$$

If input separability is assumed, then X can be considered the product of an input aggregator function of fishing effort and resource stock. Alternatively, if the resource stock is assumed to be a technological constraint rather than a factor input, then with input separability X can be considered as fishing effort.

GENERALIZED QUADRATIC FUNCTIONAL FORM

An alternative and more general specification of the revenue function is provided by the generalized quadratic revenue function:

$$\Psi (S) = \phi(a) + \sum_{i \varepsilon m} b_i \phi_i(p_i) + \sum_{j \varepsilon n} c_j \phi_j(x_j)$$

$$+ 1/2 \sum_{i \varepsilon n} \sum_{u \varepsilon n} b_{i,u} \phi_i(p_i) \phi_u(p_u) + 1/2 \sum_{j \varepsilon n} \sum_{v \varepsilon n} c_{j,v} \phi_j(x_j) \phi_v(x_v)$$

$$+ \sum_{i \varepsilon m} \sum_{j \varepsilon n} d_{i,j} \phi_i(p_i) \phi_j(x_j) \; . \qquad (21)$$

Conditional or revenue-maximizing variable product supply correspondences are easily obtained by applying Hotelling's Lemma.

CONCLUSION

Static fisheries production analysis based on-the neoclassical theory of the firm affords expanded modeling opportunities and richer, more complete information concerning the technology of firms and the industry. Not only are the obtained results consistently based on neoclassical production theory, but the potential disaggregation of aggregate indices allows useful information to be provided to policy makers and analysts. The possible insights into fisheries characterized by multiple species, cohorts, sexes, sizes, areas fished, or market categories may be especially fruitful. Increasingly, fewer hypotheses need to be maintained, thereby allowing more complete and unbiased analysis of technology.- The development of duality theory also widens the range of characteristics of technology examined. In particular, insights are provided into the nature of substitution and transformation relationships between various combinations of inputs and outputs; comparative statics effects at a point; the nature of economies of size; the nature of technical change; the nature of joint production; and characteristics such as homotheticity, homogeneity, separability, and aggregation.

This increase in information has been attained by relaxing the restrictions on aggregation of the composite output index and composite input index, fishing effort, and restrictions embodied within nonflexible forms such as the Cobb-Douglas or CES. However, this relaxation has been attained only by imposing severe restrictions on the population dynamics. A concurrent behavioral hypothesis is also generally required to obtain mathematical and statistical tractability. (In contrast, even more stringent restrictions are concurrently imposed on both the biological and economic models to provide the requisite tractability in dynamic, or capital-theoretic, models.) Finally, the approach discussed here should be recognized as having all of the limitations to any static supply-side production modeling.

Several additional areas of research are suggested by the above discussion. Disequilibrium models of input demand and product supply are certainly a distinct possibility. In these models, an attempt is made to drop the assumption of equilibrium which underlies the model of the firm described above. Instead, the focus is shifted toward the process of moving from one state to another. Another natural extension of the neoclassical theory of the firm would explicitly consider risk and uncertainty, an important issue in commercial capture fisheries.

REFERENCES

AGNELLO, R. J., and L. G. ANDERSON.

1979 Production function estimation for multiple product fisheries. Paper presented to the Eastern Economics Association, Boston, May 1979.

1981. Production responses for multi-species fisheries. Can. J. Fish. Aquat. Sci. 38:1393-1404.

BELL, F. W.

1967. The relation of the production function to the yield on capital for the fishing industry. In F. W. Bell and J. E. Hazleton (editors), Recent developments and research in fisheries. Oceana Publications, New York.

BUCHANAN, N.

1978. The fishing power of Scottish inshore white fish vessels. White Fish Authority, Fishery Economics Research Unit, Edinburgh, Occasional Paper Series, NO. 1, 29 p.

CARLSON, E. W.

1973. Cross section production functions for North Atlantic groundfish and tropical tuna seine fisheries. In A. A. Sokoloski (editor), Ocean fishery management. Natl. Mar. Fish. Serv., Seattle.

CLARK, C. W.

1976. Mathematical bioeconomics: the optimal management of renewable resources, Wiley Interscience, New York.

COMITINI, S., and D. S. HUANG.

1976. A study of production and factor shares in the halibut fishing industry. J. Polit. Econ. 75(4):366-372.

1971. Licensing and efficiency: an empirical study of the Japanese tuna fishing industry. Malays. Econ. Rev. 16, April.

COMITINI, S.

1978. An economic analysis of the state of the Hawaiian skipjack tuna fishery. Univ. Hawaii, Honolulu, Sea Grant Tech. Rep. TR-78-01, 46 p.

DIEWERT, W. E.

1973. Functional forms for profit and transformation functions. J. Econ. Theory 6: 284-316.

1974. Functional forms for revenue and factor requirement, functions. Int. Econ. Rev. 15(1):119-130.

FUSS, M.

1977. The demand for energy in Canadian manufacturing: An example of the estimation of production structures with many inputs. J. Econometrics 5:89-116.

FUSS, M., D. MCFADDEN, AND Y. MUNDLAK.

1978. A survey of functional forms in the economic analysis of production. In M. Fuss and D. McFadden (editors), Production economics: a dual approach to theory and applications, Vol. 1, Chapter II. 1. North Holland Press, Amsterdam.

GERHAPDSEN, G. M.

1952. Production economics in fisheries. Rev. Economia 5(1): 1-12.

GORDON, H. S.

1954. The economic theory of a common-property resource: the fishery. J. Polit. Econ. 62(2):124-142.

GRIFFIN, W. L., M. L. CROSS, and J. P. NICHOLS.

1977. Effort measurement in the heterogeneous Gulf of Mexico shrimp fleet. Texas A.& M. University, Department of Agricultural Economics, Technical Report No. 77-5, 33 p.

GRILLICHES, Z.

1957. Specification bias in estimates of production functions. J. Farm Econ. 39:8-20.

HANNESSON, R.

Undated. Frontier production functions in some Norwegian fisheries. University of Bergen, Norway, Department of Economics, Working Paper.

1983. Bioeconomic production function in fisheries: theoretical and empirical analysis. Can. J. Fish. Aquat. Sci. 40:968-982.

HENDERSON, J: V., and M. TUGWELL.

1979. Exploitation of the lobster fishery:' some empirical results. J. Environ. Econ. Manage. 6(4):287-296.

HOCH, I.

1962. Estimation of production function parameters combining time-series and cross-section data. Econometrica 30(1):34-53.

HOLT, S.

1982. Optimal technological progress and fishing behavior: the California swordfish fishery. San Diego State University, Center for Marine Studies, 23 p.

HUANG, D. S., and C. W. LEE.

1976. Toward a general model of fishery production. Southern Econ. J. 43(1) :846-854.

HUPPERT, D. D.

1975. Economics of a multi-species fishery: theoretical and empirical results for the Washington coastal trawl fleet. Ph.D. Thesis, Univ. Washington, Seattle.

HUSSEN, A., and J. G. SUTINEN.

1979. Estimation of production functions for the artisanal fishery for the Gulf of Nicoya (Costa Rica). University of Rhode Island, Kingston, International Center for Marine Resource Development, Working Paper No. 1, 36 p.

JACOBSEN, S. E.

1970. Production Correspondences. Econometrica 38(5):754-771.

KIRKLEY, J., and I:. STRAND, JR.

1981. Bioeconomic concepts and applications in fisheries production. Unpubl. manuscr. Northeast Fisheries Center, National Marine Fisheries Service, NOAA, Woods Hole, MA 02543.

KIRKLEY, J.

1982. Analyzing production in fisheries: theoretical and empirical concerns of production in single and multispecies fisheries. In J. Conrad, J. Kirkley, and D. Squires, Lectures on the economics of fisheries production. National Marine Fisheries Service, Seattle.

LAITINEN, K.

1980. A theory of the multiproduct firm. North Holland Press, Amsterdam.

LAU, L. J.

1978. Applications of profit functions. In M. Fuss and D. McFadden (editors), Production economics: a dual approach to theory and applications, Vol. 1, Chapter 1.3. North Holland Press, Amsterdam.

LIAO, D. S.

1975. Profitability and productivity analysis for the southeastern Alaska salmon fishery. U.S. Natl. Mar. Fish. Serv., Mar. Fish. Rev. 38(4):11-14.

LOPEZ, R. E.

1981. Estimating substitution and expansion effects using a profit function framework. University of British Columbia, Vancouver, Department of Agricultural Economics, Discussion Paper No. 8003, 29 p.

MACSWEEN, I.

1973. Measurement of fishing power. White Fish Authority, Fishery Economics Research Unit, Edinburgh, Miscellaneous Reference Paper.

MCFADDEN, D.

1978. cost, revenue, and profit functions. In M. Fuss and D. McFadden (editors), Production economics: a dual approach to theory and applications, vol. 1, Chapter I.1. North Holland Press, Amsterdam.

MUNDLAK, Y.

1961. Empirical production function free of management bias. J. Farm Econ; 43:44-56.

NADIRI, I. M.

1982. Producers theory. In K. J. Arrow and M. D. Intriligator, Handbook of mathematical economics, Vol. 2, Chapter 10. North Holland Press, Amsterdam.

OMAR, I. H.

1983. Malaysian trawlers: economics of vessel size. Mar. Policy 7(3):220-222.

ROTHSCHILD, B. J.

1972. An exposition on the definition of fishing effort. U.S. Natl. Mar. Fish. Serv., Fish. Bull. **70:671-679:**

SAKAI, Y.

1974. Substitution and expansion effects in production theory: the case of joint production. J. Econ. Theory 9:255-274.

SCOTT, A.

1955. The fishery: the objectives of sole ownership. J. Polit. Econ. 63(2):116-124.

SIEGEL, R. A., J. J. MUELLER, and B. J. ROTHSCHILD.

1955. A linear programming approach to determining harvesting capacity: a multiple species fishery. U. S. Natl. Mar. Fish. Serv., Fish. Bull. 63:116-124.

SOLOW, R. M.

1955-56. The production function and the theory of capital. Rev. Econ. Studies **23:101-108.**

TAYLOR, T. G. and F. J. PROCHASKA.

1981. Fishing power functions in aggregate bioeconomic models. University of Florida, Gainesville. Department of Food and Resource Economics, Staff Paper 185, 13p.

THEIL, H.

1980. The system-wide approach to microeconomics. Univ. Chicago Press, Chicago.

VARIAN, H. R.

1978. Microeconomic analysis. Norton, New York.

WILSON, J. A.

1982. The economical management of multispecies fisheries. Land Econ. 58(4):417-434.

ZELLNER, A., and N.S. REVANKAR.

1969. Generalized production functions. Rev. Econ. Studies 36:241-250.

AN EMPIRICAL ANALYSIS OF PRODUCTION IN

SINGLE AND MULTISPECIES FISHERIES

BY JIM KIRKLEY

INTRODUCTION

An examination of the economics of production in fisheries is often complicated. Outputs and inputs are seldom well defined or easily measured. Appropriate information for aggregation and conducting time series and cross-section analyses is limited. Many single-species fisheries may be multiple-output fisheries due to market characteristics such as size and/or sex. The exact technology is unknown and assumed restrictions and conditions may be inadequate. These limitations need to be considered when examining the technology.

This section attempts to demonstrate 1) many of the problems of empirically examining the production technology, 2) the need for rigorous examination of data, 3) the types of information which may be derived even with limited information, 4) the restrictive conditions often imposed on the technology by various assumptions, and 5) the need for an "economic" framework for examining the production correspondences. Three examples based on the New England groundfish/otter trawl fishery are presented to illustrate concepts. A time series model based on spatial separability of stocks between Georges Bank and other areas is presented; a cross section model for 1980 is considered and its-derived results are compared to those based on a financial simulator (Mueller and Kurkul 1982); and a revenue function based on the principles of duality is considered (Diewert 1974a,b).

THE NEW ENGLAND GROUNDFISH/OTTER TRAWL FISHERY: A TIME SERIES ANALYSIS WITH A SINGLE-SPECIES APPROACH

The New England trawl fishery is mixed. The application of factor inputs typically yields more than one output as more than 50 species are harvested by trawls (Murawski et al. 1982). Those of primary importance in terms of first sale value include cod, haddock, yellowtail flounder, winter flounder, redfish, and assorted other flounders (Table 1). Many of the species also are marketed by size, thus increasing' the number of outputs. Trawl activity accounts for more than 85% of the landed value of major finfish species by all gear (Table 2). There are three basic stock areas of commercial activities: 1) Gulf of Maine, 2) southern New England, and 3) Georges Bank (Resource Assessment Division).' Each of the species/stocks appear to display both short and long run seasonality as a result of weather, recruitment, availability, and demand conditions (Tables 3, 4).[2] Vessel sizes prosecuting the fishery range in size from less than 5 tons to more than 400 tons with corresponding crew sizes between 1 and 14 (Table 5). More than 30 inputs are used in harvesting groundfish. Consequently, there is substantial heterogeneity among the fleet, outputs, inputs, stocks, and seasons, all considerably complicating an empirical analysis.

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[1]There are possibly more since some species may have more than one distinct stock in an area. Excluded are the mid-Atlantic stocks which are occasionally exploited by New England trawlers.

[2]A rigorous examination of seasonality is not pursued in this paper. Seasonal indices are based on exponential smoothing. A more rigorous examination is found in Kirkley et al. (1982)

[3]Inputs are considered within the framework assumed by Department of Agriculture; see Kirkley (1978) and (1981).

Table 1. Landings and value of selected species taken by U.S. fishermen in the northwest Atlantic otter trawl fishery, 1965-80.

ANNUAL SPECIES SUMMARY

Year	Cod	Haddock	Whiting	Flounder	Yellow	Hake	Pollock	Lobster	Scallop	Redfish	Herring	Total
Landings												
65	13538.07	58861.87	32623.52	15108.29	34664.27	2242.51	4914.20	1710.71	5.25	37929.87	191.42	243002.08
66	13671.08	48083.79	35751.27	17847.74	28660.62	1229.16	3542.95	155.13	.54	36987.85	225.56	231600.67
67	16655.57	43231.62	26227.03	15568.97	23721.56	885.68	2687.75	1415.88	4.12	32389.76	202.65	209325.74
68	17986.64	31194.77	31511.65	12914.93	29101.05	1081.67	2557.43	1561.37	.45	27813.51	210.04	203040.39
69	22054.81	19510.58	16748.27	15080.09	29269.51	1375.11	3772.31	1548.58	14.34	25315.84	3510.43	185568.72
70	19633.55	11378.18	17543.53	15864.83	30149.92	2039.90	3552.55	1387.68	19.31	25075.04	9023.56	171601.60
71	18506.68	9019.64	12199.52	15614.87	24306.38	2414.74	4355.09	1056.70	22.28	27196.07	15585.88	155321.57
72	15455.85	4605.90	8067.77	12928.85	28750.34	2475.41	4902.47	624.76	11.31	26664.52	10911.08	134554.40
73	17116.31	3326.58	15394.19	11782.81	26757.64	2265.06	4959.29	300.26	19.06	23989.31	1097.51	134329.44
74	20537.36	3412.46	9206.24	10447.29	23950.83	2414.15	6187.14	616.56	15.56	18649.40	1155.21	123220.63
75	19119.59	6970.84	14991.94	13494.62	18713.31	2096.22	5817.68	554.91	79.32	14510.42	739.25	115420.92
76	19436.55	5379.05	16717.96	13226.79	16712.63	2359.56	6867.72	486.29	360.61	14556.46	253.18	115437.45
77	28133.73	12019.49	14827.79	20090.52	15925.05	2767.78	7362.26	323.56	70.14	15844.61	357.06	134731.61
78	30328.46	16688.01	15665.01	24565.59	10545.37	2895.08	9247.49	449.47	42.23	16071.02	703.20	145316.34
79	34569.39	17537.76	7175.67	24841.86	14571.22	3244.00	7675.40	375.08	34.88	15370.55	1922.80	152869.88
80	41129.17	22183.69	7719.02	31393.02	17115.22	3201.89	10364.71	249.06	153.02	10635.24	648.88	165844.12

Table 1. Cont'd.

ANNUAL SPECIES SUMMARY

Year	Cod	Haddock	Whiting	Flounder	Yellow	Hake	Pollock	Lobster	Scallop	Redfish	Herring	Total
Value												
65	2395450	13139864	1810458	3418659	7118548	201398	674546	2194494	8861	3395468	17021	36600709
66	2586021	13370759	3406101	4590706	7750005	149565	459251	227953	580	3424365	17388	38546711
67	3021781	10726121	1602345	3970732	5452700	113305	349221	2427607	7999	2799363	18818	33717107
68	2898228	9064417	2261959	3615939	6562051	128113	345488	2949082	1108	2376686	24968	33742441
69	4192872	7306201	2050246	4457824	8529628	157046	478977	2992089	35835	2365609	133462	37604442
70	4777709	5630622	3271975	5245320	9775428	254324	636354	2889587	56300	2724883	390258	41489138
71	5098067	5141753	1549544	5598204	8369461	309476	751462	2465375	65210	3046302	605563	38473600
72	6221478	3689497	1636895	6473955	11667405	431255	1002971	1917719	47871	3288935	476883	42145296
73	6899479	2717160	2289060	6195768	12734003	463402	1187399	1007319	77850	4067557	83544	46157839
74	8919077	2693986	1627829	5925377	13364972	462286	1529808	2255039	51633	3318656	87385	49093988
75	10149262	4937090	2748690	9390802	14617662	452580	1695706	2105644	318932	3298005	55509	57860618
76	11366344	5098954	2912730	10305484	15192784	805814	2173544	2007853	1307579	4387928	24815	65348495
77	13793430	8460779	2782122	15803447	16563711	934212	2411750	1491460	221945	5342388	45879	75055295
78	16742133	11671633	4653776	23210873	14169897	1175792	3594521	2209469	230796	6066130	113192	93416891
79	23067903	16385236	2707764	22658452	16377461	1381692	3490357	1750956	261924	7134761	300708	107572789
80	25452486	18962052	2820986	25621153	17968025	1399500	4470661	1287761	1507387	5386132	118562	116277485

Table 2. Landings and value of selected species taken by U.S. fishermen in the northwest Atlantic, all gear, 1965-80.

ANNUAL SPECIES SUMMARY

Year	Cod	Haddock	Whiting	Flounder	Yellow	Hake	Pollock	Lobster	Scallop	Redfish	Herring	Total
Landings												
65	14386.52	59663.51	32623.73	15136.32	34691.87	2327.48	5129.85	1764.58	5510.54	37930.59	1123.66	257186.90
66	14891.49	58790.78	35838.09	17910.19	28722.87	1356.28	3872.52	1245.26	4963.80	36988.92	2475.02	248372.10
67	17541.48	43712.79	26227.67	15588.31	23725.92	951.35	3107.47	1415.88	3106.80	32389.76	2484.47	223002.26
68	19188.17	31406.90	31514.74	12938.20	29158.44	1189.12	2989.19	1597.39	3502.03	27813.51	9957.94	221066.51
69	23022.30	19910.97	16748.35	15098.54	29354.90	1479.72	3940.23	1678.36	2245.63	25315.84	6148.36	196120.26
70	20706.10	11648.41	17543.60	15876.82	30170.07	2181.19	3850.71	1520.38	1943.97	25075.04	13866.60	188448.25
71	19718.72	9273.06	12200.25	15722.26	24422.74	2600.10	4646.56	1294.21	1795.63	27196.15	21322.20	179097.36
72	16732.70	4874.56	8178.14	13074.22	28952.59	2836.59	5388.04	2113.02	1567.37	26664.70	19894.84	164369.05
73	18344.62	3508.63	15432.61	11873.74	26892.69	2697.07	5766.56	1249.18	1427.08	24343.16	9084.98	181324.60
74	21757.43	3518.63	9217.44	10487.36	24003.08	3270.91	7434.15	1845.05	1888.81	18776.28	10697.97	177931.09
75	20473.54	7064.05	15000.46	13531.35	18764.61	3039.61	7333.10	2131.63	2494.76	14523.94	18532.77	168452.90
76	21272.12	5560.44	16760.98	13307.95	16795.68	3269.65	8953.90	2014.76	5071.39	14564.08	18209.21	175245.11
77	30358.56	12521.06	14875.47	20163.22	15996.44	4020.11	11000.79	1788.48	7114.85	15864.20	17738.97	188908.51
78	33036.55	17349.82	15814.95	14866.63	10830.96	4147.85	15034.22	2197.44	7541.80	16090.58	20624.65	227184.23
79	37085.42	18198.81	7206.56	25154.22	15203.32	4199.89	13156.30	1881.42	6892.21	15408.06	24747.97	235444.98
80	44336.10	23484.80	7768.90	31852.40	17973.76	4066.11	14962.58	1435.98	6966.71	10671.61	31286.25	266318.15

Table 2 Cont'd.

ANNUAL SPECIES SUMMARY

Year	Cod	Haddock	Whiting	Flounder	Yellow	Hake	Pollock	Lobster	Scallop	Redfish	Herring	Total
Value												
65	2540423	13382284	1810498	3427567	7122818	214463	706460	2282261	8229271	3395532	44185	46033339
66	2806326	13607780	3418625	4606742	7763212	168706	499605	1916198	5393745	3424434	88026	47116480
67	3163735	10867210	1602380	3977323	5453418	119982	394423	2427607	5300740	2799363	83215	39987100
68	3040792	9130010	2262336	3624428	6570365	137150	383737	3008920	8636042	2376686	239405	43415896
69	4342636	7475150	2050263	4465055	8541795	167366	499097	3242664	5474670	2365609	196282	44431054
70	4993029	5777217	3271992	5250361	9783155	270077	676800	3161692	5810950	2724883	554067	48880856
71	5382605	5311588	1549640	5639745	8395159	334578	792260	3007167	5854493	3046316	801886	46470714
72	6617028	3929010	1670614	6542486	11726156	483278	1082974	6200137	6923345	3288958	848833	55440824
73	7378623	2902186	2293849	6236616	12791701	544010	1331029	4353061	5600842	4130977	559053	59389884
74	9400175	2809120	1629590	5947385	13396861	625949	1776949	6839517	6449107	3341747	749070	66453903
75	10759526	5022893	2750334	9413482	14658156	654100	2008714	8479349	10391158	3300839	1202662	83590335
76	12326619	5298035	2920554	10364738	15270798	1103535	2681874	8137191	20607667	4390344	1298863	100739434
77	14995668	8937487	2792550	15854965	16637534	1346269	3482083	7815645	25846887	5348689	1452833	116318202
78	18052130	12227343	4689507	23515953	14556808	1659378	5679152	10293996	42274498	6073340	3008603	164486112
79	24424482	16982089	2719119	22934336	16982650	1746681	5659962	9169907	51668672	7151043	3841019	189938562
80	27157193	20110251	2838537	25962003	18747387	1744116	6180760	7605887	59031459	5404495	3957453	204348530

Table 3.--Seasonal factors of commercial catch (per ton day fished) during the Georges Bank otter trawl fishery by month.[a]

Month	Cod	Flounders	Haddock	Hakes	Pollock	Redfish	Whiting	Yellowtail
Jan	0.78	0.65	1.00	1.01	1.68	0.75	0.06	1.17
Feb	1.94	0.58	1.06	0.74	1.27	1.54	0.05	0.99
Mar	1.07	0.76	0.98	0.85	0.78	1.92	0.07	0.97
Apr	1.13	1.16	1.05	0.56	0.60	1.71	0.11	0.72
May	1.16	1.62	1.30	0.55	0.58	1.99	0.47	0.63
Jun	1.20	1.31	1.40	0.91	0.63	1.07	0.73	0.74
Jul	0.95	1.12	1.00	1.03	0.59	0.71	3.78	1.00
Aug	0.88	0.89	0.91	1.09	0.82	0.56	3.82	1.25
Sep	0.98	0.98	0.88	1.01	0.94	0.45	1.85	1.27
Oct	1.11	1.02	0.89	1.51	0.88	0.43	0.78	1.13
Nov	0.86	1.09	0.76	1.52	1.38	0.40	0.22	1.06
Dec	0.77	0.82	0.77	1.22	1.86	0.48	0.07	1.06

[a]Derived by exponential smoothing, first differences.

Table 4.--Relative abundance (k per tow) of selected species during the Georges Bank survey, 1965-80.[a]

Species	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Cod	7.2	5.0	8.4	5.3	4.9	7.8	6.1	14.2	19.1	5.1	8.53	10.9	11.54	21.46	15.2	6.2
Haddock	56.1	21.4	20.5	9.3	5.8	10.6	3.6	5.1	7.2	2.8	2.56	27.55	23.78	11.83	25.21	11.91
Redfish	1.1	2.0	2.6	3.5	6.5	4.6	1.9	3.9	2.6	1.9	5.08	.64	5.84	5.6	4.51	.35
Silver hake	1.6	2.1	1.0	2.2	1.6	2.3	1.2	2.4	2.4	1.5	2.25	5.29	1.98	4.57	1.99	3.81
Pollock	1.7	2.9	1.1	1.0	1.4	.4	2.2	1.0	1.6	.4	1.78	31.35	3.23	2.97	2.10	1.97
Red hake White hake	2.6	11.2	2.4	2.1	3.3	3.3	4.1	3.4	6.3	3.4	7.93	5.66	7.22	7.83	4.35	11.13
Yellowtail	5.6	2.5	4.5	6.7	5.4	3.0	3.7	4.0	3.8	2.2	1.36	1.17	3.16	1.9	1.39	4.97
Other flounders	4.3	9.5	4.7	4.9	4.6	8.1	3.0	4.7	7.5	4.1	4.7	7.21	9.85	8	6.55	7.86
Other Groundfish	9.8	11.0	3.4	6.8	14.4	6.2	13.8	5.2	6.7	13.4	6.83	5.20	9.44	9.11	8.04	7.52

[a]Determined by survey weight (kilos) per tow (Clark and Brown 1981).

Table 5.--Selected characteristics of the northwest Atlantic otter trawl fleet, 1976-80.[a]

Year	Number of vessels	Tonnage distribution: Number			Tonnage distribution: Range			Horsepower			Crew Size			Landings	Value	Average price
		≤50	51-300	>300	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	lbs	$	$/lb.
76	590	311	270	9	7	67	483	15	288	1300	1	4	13	243829264	64693804	.27
77	594	287	298	9	8	70	483	50	307	1300	1	4	13	281816231	74930514	.27
78	625	326	290	9	7	67	483	50	302	1300	1	4	13	302399410	92506115	.31
79	757	404	344	9	7	66	483	24	309	1300	1	4	13	316831054	106885263	.34
80	846	426	412	8	8	70	483	35	340	1300	1	4	14	317197260	106727374	.34

[a]Under tonnage vessels (<5 tons) are excluded.

The problems, of heterogeneity have often been considered by examining conditons of separability and aggregation. Separability conditions enable the problem to be structured in a multistage context and enable aggregates to be considered.[4] Aggregation reduces the number of variables in the problem (e.g., 30 inputs are aggregated to form the composite input-effort). However, in the following empirical analysis these important concerns were ignored. Input-output separability was imposed and aggregates were formed without further consideration.[5]

The aggregate production technology and corresponding resource functions were specified as follows:

$$Q_t = \alpha_o TDF^{\alpha_1} CDA^{\alpha_2} \exp^{B_1 RA_t + B_2 D_2 RA_t + \ldots + B_{12} D_{12} RA_t + U_t} \qquad (1)$$

$$RA_t = \alpha_o \; \alpha_1 Q_{t-1} + \ldots + \alpha_6 Q_{t-6} + B_1 RA_{t-1} + B_2 R_{t-12} + V_t \, , \qquad (2)$$

where Q wasmonthly total physical output by otter trawl, TDF was the sum of the product of tons and days fished, CDA the sum of the product of crew size and days absent, RA an instrument for monthly resource availability, D a vector of monthly dummy variables, t-i the time period (t-l ,...,12), and Ut and V_t the disturbance terms.[6]

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[4]Other important implications for separability and aggregation are discussed in McFadden (1978) and Blackorby et al. (1978).

[5]A preliminary analysis by D'Addiio and Kirkley (1981) of daily prices of selected species by size based on the composite commodity theorem (Hicks) within the framework of Diewert (1976) suggested that average daily price movements among cod, haddock, yellowtail, and winter flounder, by size and species, were not statistically different. This was compatible with the market demand specification assumed by Bockstael (1977). However, this is an inexact test and additional analysis is required.

[6]In actuality, all right-hand side variables were instrumental variables; TDF for the capital aggregate, CDA for the labor aggregate, and RA is resource size and abundance. The geometric product was not considered (see Theil (1954)) nor was the possible correlation of U_t and Vt. Equation (2) was considered within a time-series approach to deal with non stationarity and heteroscedasticity.

Estimation was based on a quasi-transcendental specification with output and factor inputs being Cobb-Douglas and monthly resource availability specified as exponential. Data on outputs and inputs aggregates were monthly for the period 1965-80. Resource availability was derived by applying monthly seasonal factors of commercial catch per ton day fished to the survey weight per tow of selected species (Kirkley 1982). Estimates and statistical results are in Tables 6 and 7.

Estimation of equations (1) and (2) was accomplished by single equation methods. Equation (2) was subjected to an exogenity test because of the implied equation (Q_{t-1} and RA_{t-}, by using the fitted values ($\hat{Q}_{t-1}$) obtained by regressing Q_t on all exogenous variables and an instrumental variable (CDA) (Hausman 1978). The results indicated that Qt-1 and RAt-1 could both be considered as exogenous variables in equation (2). Equation (1) was estimated by correcting for an autogressive disturbance of order 1 and 12 (moving average in Box-Jenkins terminology). Equation (2) was initially estimated with 12 lags but the 7th-12th were insignificant. Biological information suggested a declining lag which approximates the Koyck lag structure. The imposed serial correlation was corrected by using the Cochran-orcutt technique combined 'with the constrained Almon lag structure.

The results of equations (1) and (2) provide a limited analytical framework of the production technology. Limitations are the result of 1) implied input separability, 2) aggregation of outputs, and 3) uncertainty about the resource availability. Determination of the species composition requires 'the assumption that prior compositions will prevail or that the ratios (compositions) can be predicted (Table 8). The model could be improved by estimating two additional equations for each species which specify the composition as a function of resource availability and effort, and effort as a function of expected prices and costs.

Table 6.--Production response estimates and statistics[a].

	Constant α_0	TDF α_1	CDA α_2	RA B_1	D3RA B_3	D4RA B_4	D5RA B_5	D6RA B_6	D7RA B_7	D8RA B_8	D9RA B_9	D10RA B_{10}	D11RA B_{11}
Parameter estimates	.158	.327	.689	-.0015	.0017	.0019	.0036	.005	.0063	.0065	.0059	.0042	.0019
Standard error		.13	.14	.0017	.001	.001	.001	.001	.001	.001	.001	.001	.0008
Adjusted R^2	.92												
Durbin Watson	2.24												

[a]Estimated by instrumental variables and corrected for autoregressiveness of the residuals ($U_t = P_1 U_{t-1} + P_2 U_{t-12}$)

Table 7.--Resource availability response estimates and statistics[a].

	Constant α_0	Landings t-1 α_1	Landings t-2 α_2	Landings t-3 α_3	Landings t-4 α_4	Landings t-5 α_5	Landings t-6 α_6	Resource availability t-1	Resource availability t-12
Parameter estimates	8.14	-.00032	-.00031	-.0003	-.00029	-.00028	-.00027	.89	.11
Standard error	1.9	.00015	.0001	.000065	.00006	.00009	.00013	.03	.03
Adjusted R^2	.9								
Durbin Watson	1.73								

[a]Almon lag polynomial of degree 2 based on biological assumptions that landings in most recent period have largest effect on current resource availability. Note the approximation of agrometric lag. Estimation by combined Cochran Orcutt-Almon lag procedures.

Further examinations of the results suggest constant returns to scale in the variable inputs; resource availability is considered as a technological contraint which shifts the production possibilities. The' seasonality indicated by the dummy variables' slope estimates is consonant with biological expectations. Inclement weather conditions control harvesting more during the winter period (December-February). The summer months' exhibit the combined effects of resource availability, recruitment, and better weather. The elasticity of substitution for equation (1) is not particularly interesting; the Cobb-Douglas yields unitary elasticity of substitution.

Although not calculated but of significant interest is the Allen partial elasticity of substitution of each input with respect to the monthly resource availability. The exponential nature of resource availability does not give constant unitary elasticity; however, the total elasticity may be preferable. However, the exact nature is uncertain. Both complementarity and competitiveness probably would be indicated over different ranges of resource availability. Indicated by this elasticity is the ability to increase inputs (controllable) in response to a declining resource. Appropriate analysis would require additional information on costs, and the appropriateness of using the partial elasticity.

In summarizing the empirical analysis of the Georges Bank otter trawl fishery, it is viewed as an extremely complicated problem.: There is 1) the problem of defining inputs and outputs; 2) deriving measures of resource availability and abundance; 3) examining the necessary separability conditions; 4) testing for aggregation of both outputs and inputs; 5) determining the natural and economic periodicity of the fishery; 6) specifying a functional form and structure of equations; 7) estimating and statistically validating the equations and results; and 8) deriving the economic parameters of interest

Table 8.--Species composition (%) of the western Georges Bank otter trawl fishery by month, 1978-80.

Date	Cod	Haddock	Whiting	Flounder	Yellowtail	Hake	Pollock	Lobster	Scallops	Redfish	Herring
1/80	0.34	0.14	0.00	0.11	0.32	0.00	0.05	0.00	0.00	0.02	0.00
2/80	0.32	0.13	0.00	0.10	0.31	0.00	0.06	0.00	0.00	0.02	0.00
3/80	0.36	0.13	0.00	0.10	0.25	0.01	0.07	0.00	0.00	0.02	0.00
4/80	0.43	0.18	0.00	0.14	0.14	0.00	0.05	0.00	0.00	0.01	0.00
5/80	0.41	0.20	0.00	0.16	0.09	0.01	0.08	0.00	0.00	0.02	0.00
6/80	0.44	0.18	0.01	0.13	0.08	0.03	0.09	0.00	0.00	0.02	0.00
7/80	0.36	0.22	0.02	0.13	0.11	0.02	0.07	0.00	0.00	0.05	0.00
8/80	0.32	0.17	0.01	0.19	0.14	0.01	0.08	0.00	0.00	0.05	0.00
9/80	0.35	0.17	0.05	0.18	0.11	0.01	0.06	0.00	0.00	0.04	0.00
10/80	0.41	0.12	0.03	0.20	0.11	0.01	0.06	0.00	0.00	0.03	0.00
11/80	0.31	0.19	0.01	0.22	0.10	0.02	0.09	0.00	0.00	0.04	0.00
12/80	0.31	0.20	0.00	0.22	0.17	0.01	0.05	0.00	0.00	0.01	0.00

(e.g., the partial elasticities of substitution). Particularly limiting to these results is the inadequate treatment of the multiple outputs. Consequently, corresponding results can only be considered as limited approximations. Additional analysis should include investigation of the flexible functional forms (Diewert 1973; Denny 1974; and McFadden 1978), inclusion of costs, utilization of alternative estimation procedures, and examination via the costs or profit function approach for multiple outputs (Hall 1973; Diewert 1973).

THE NEW ENGLAND OTTER TRAWL FISHERY: A CROSS SECTION ANALYSIS (1980) WITH A SINGLE SPECIES APPROACH

In this section, a cross-sectional analysis of the otter trawl production technology for 1980 is presented. It differs from the preceding analysis in that 1) it is a cross-sectional examination; 2) analysis is restricted to port side activities ignoring area concerns; 3) annual aggregates by vessels comprise the unit observations; 4) technological constraints imposed by either the ecological or spatial aspects are not explicitly considered; and 5) more "economic type" information is desired.

As in the preceding analysis, the problems of separability, aggregation, and multiple outputs are ignored. An "exact" representation of the technology is assumed and considered to be the transcendental form. The transcendental allows for nonconstant returns to scale and variable elasticities of substitution. Desired from this analysis are estimates of the technology, input substitution possibilities, elasticity of scale, returns to scale, and returns to factor inputs. Also desired is a comparative analysis between returns to factor inputs as determined by the technology and those estimated by a financial simulator.[7]

In 1980, there were 846 vessels using a trawl in New England. This includes both full- and part-time activities. Gross income per vessel ranged from \$37 to \$1,081,668. Correspnding ranges for number of trips, days absent, and days fished were 1 to 195, 1 to 252, and 1 to 153.2, respectively. Several vessels were intermittent or transient otter trawl operators, i.e., they switched fisheries during the year. However, the exact number cannot be readily verified due to limited data and inadequate assignment rules. Information available for the analysis included total output and value, vessel tonnage, crew size, days absent, days fished, engine horsepower, vessel age, length, port of operation, and port specific lay systems. Available from Mueller and Kurkul (1982), and further modified were various estimates of fixed and variable costs.

The transcendental function estimated was

$$Q_i = \alpha_o \, TDF_i^{\alpha_i} \, CDA_i^{\alpha_2} \exp^{B_1 TDF_i + B_2 CDA_i + U_i} \tag{3}$$

where variables are defined as in the preceding discussion but measured for the ith vessel during 1980. The estimates and statistics were

$$Q_i = (264.4) \underset{(.04)}{TDF^{.342}} \; \underset{(.058)}{CDA_i^{.775,}} \; \exp^{-\underset{(.000008)}{(.000019)}TDF_i - \underset{(.00011)}{.00022}CDA_i} \quad \bar{R}^2 = .9 \, , \tag{4}$$

where numbers in parenthesis are the standard errors.[8] Economic parameters of concern on a per vessel basis are summarized in equation form:

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[7]The simulator is described in Mueller and Kurkul 1982. Modifications to the simulator-generated cost data were done to deal with smaller vessels.

[8]Estimation was accomplished by generalized least squares due to an apparent relationship between ton days fished and the error variance. Errors were assumed $N(0,U^2)$ rather than $N(Uu,a^2)$ (i.e., the average vs. the frontier).

the functron coefficient (E) or local measure of returns to scale

$$\varepsilon = \sum_{i=1}^{2} (\alpha_i + B_i X_i) , \tag{5}$$

marginal products (MPi)

$$MP_i = Q_i \left(\frac{\alpha_i}{X_i} + B_i \right) , \tag{6}$$

average products (APi)

$$AP_i = Qi/Xi , \tag{7}$$

implied input prices given assumptions Ai

$$IR_i | A_1 \text{ (Profit } \underline{\text{MAX.}}) = P_o \cdot Q[\alpha_i/X_i + B_i]$$

$$IR_i | A_2 \text{ (Cost } \underline{\text{MIN.}}) = (IR_j \cdot \ | \text{(Profit } \underline{\text{MAX.}}) \ [(\alpha_i/X_i + B_i)/(\alpha_j/i_j + 6_j)]$$

$$IR_i | A3_i \varepsilon \ > 1 \text{ (Profit=O)} = [P \cdot Q - (IR_j \cdot X_j \quad \text{Profit=O}]/X_i , \tag{8}$$

rate of technical substitution (RTS)

$$RTS_i = (\alpha_i + B_i X_i / \alpha_j + B_j X_j) \quad (X_j / X_i) , \tag{9}$$

elasticity of substitution (a.)

$$\sigma = \frac{(B_1 + \alpha_1 X_1^{-1}) (B_2 + \alpha_2 X_2^{-1}) [(B_1 + \alpha_1 X_1^{-1}) X_1 + (B_2 + \alpha_2 X_2^{-1}) X_2}{[(\alpha_2 X_2^{-2}) (B_1 + \alpha_1 X_1^{-1})^2 + (\alpha_1 X_1^{-2}) (B_2 + \alpha_2 X_2^{-1})^2]} , \tag{10}$$

where X_i, X_j are the factor inputs, Q is output, P_0 is output price, and IR_i are implied prices derived from three behavioral assumptions.

A summary of ranges of values for the parameters of interest are presented in Table 9. They are by arbitrary tonnage classes. In general, the smaller vessels display increasing returns to scale and lower substitution possibilities. The larger vessels tend to exhibit decreasing returns to scale with some ability to substitute factors of production. The elasticity of substitution is important to management because it indicates the ability or ease of harvesters to substitute inputs in order to circumvent regulations. The estimated elasticities suggest that the smaller and extremely large vessels would be at least able to efficiently substitute inputs; vessels between 51 and

Table 9.--Selected economic parameters derived from the production technology, 1980.

Tonnage Class	Number of Vessels	Marginal Product (ton days fished)			Marginal Product (crew days absent)			Rate of Technical substitution			Returns to scale			Elasticity of substitution[a]			Percent		Average Price
		Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Landings	Value	
≤25	219	4.19	105.52	448.6	36.4	549.7	3195.9	.04	.22	.63	.98	1.09	1.11	.9	.92	1.01	.04	.04	.33
26-50	209	11.87	81.14	313.78	48.2	611.9	2607.0	.03	.12	.78	.82	1.03	1.11	.9	.96	1.21	.16	.15	.32
51-100	202	4.07	45.2	239.5	77.1	650.7	2816.5	.01	.07	.19	.61	.95	1.11	.9	1.07	1.62	.28	.27	.32
101-150	141	.6	19.2	129.74	36.6	527.6	1921.2	.0	.04	.15	.44	.8	1.10	.9	1.29	2.28	.31	.32	.35
151-200	64	-7.12	10.9	74.45	24.9	517.4	1622.9	-.02	.03	.17	.31	.76	1.11	.9	1.47	3.27	.16	.17	.37
201-300	3	.5	2.22	5.03	470.5	634.4	824.6	.0	.0	.01	.46	.49	.53	1.9	2.05	2.19	.02	.01	.27
>300	8	-23.64	-9.39	-1.86	81.7	370.7	729.5	-.29	-.06	-.01	-.21	.24	.48	-348.9	-41.9	4.79	.04	.04	.30
FLEET	846	-23.6	62.09	448.6	24.8	606.4	3195.9	-.29	.11	.78	-.21	.96	1.11	-348.9	-.67	4.79	---	---	---

[a]Negative elasticities are likely the result of bad data.

300 tons would likely be able to circumvent input constraints such as effort limitations by increasing the utilization of labor or labor related components. A more comprehensive examination of costs, inputs, and multiple outputs is required. Also suggested by the summary statistics in Table 9 is that the extremely large vessels appear to be operating in inefficient regions (i.e., negative marginal products). This was probably the result of management constraints in 1980 coupled with poor resource conditions and low ex-vessel prices, or a result of poor data.

An additional concern of the cross-section analysis was to compare returns to factor inputs as estimated by the technology to those estimated by the finanacial simulator given different assumptions. Appropriate comparisons could be used to indicate the objectives of harvesters and whether or not they were achieved. In addition, if returns to factor inputs obtained by the two estimates were close, then costs may be approximated and concepts of duality applied. Three basic assumptions were considered: 1) vessels displaying decreasing returns to scale were assumed to be profit maximizers, 2) those exhibiting constant or increasing returns were profit maximizers subject to a zero profit constraint, and 3) cost minimization given labor costs from profit maximization. Gross returns should be compatible if the inputs--ton days fished and man days--are adequate instruments.

Table 10 is a summary of selected returns to factor: inputs given the different assumptions. It should be noted that cost minimization and restrictive profit maximization can be demonstrated to yield the same solution (McFadden 1978). A major problem of estimating gross returns is determining the distribution of joint expenses. It is assumed that each factor's share of joint cost is equal to the net share distribution (e.g., if the crew share (α) of gross stock less joint expenses is 55%, then they

Table 10 .--Estimated factor returns based on technology and financial simulator.

GRT	Scale	Labor returns, production function	Labor returns[a] financial simulator	Vessel returns[b] production function	Vessel returns, financial simulator	Vessel returns given labor from profit max.	Vessel returns given labor from simulator
14	1.11	302	252	267	282	181	222
33	1.10	3137	2649	6989	7451	5010	5902
9	1.03	9759	8551	8961	9619	7203	6904
18	1.07	18842	16392	17007	18441	13540	14795
82	1.08	5195	4428	6824	7472	5171	5816
16	1.06	11946	10442	10838	11747	8734	9474
24	1.02	35789	32699	32534	36786	30600	29725
34	1.02	27224	24519	24046	27584	22174	21658
34	1.05	16938	14841	14959	16696	12504	13108
92	.9	15514	14809	62147	67081	44681	42652
76	.90	18449	17499	52338	57086	37800	35855
101	.77	26136	29036	128531	111125	61973	68852
99	.75	22072	24322	107395	93897	48520	53465
116	.69	22570	26870	150093	119994	53822	64076
121	.84	10357	10400	68874	67562	41345	41869
176	.89	17865	16520	65119	74537	43545	40266
151	.59	27824	34100	202948	154777	39604	49399
186	.64	30486	32800	163155	146956	26892	28933
200	.74	11532	12873	98696	83475	40864	45619
9	1.11	278	190	246	344	167	167

[a]Simulator adds captain's commission to vessel share. Labor returns is set equal to net crew share plus crew share of joint expenses plus captain's commission and crew's share of joint expenses is assumed equal to crew's share of net stock.

[b]If scale > 1, vessels returns set equal to value less total 1 above share (Labor's share x crew).

are responsible for 55% of the expenses). Gross returns were estimated as follows:

(1) Profit Maximization 1 (scale (1):

Labor's return = $(P_0 \cdot MP_{CDA})*CDA$,

Vessel's return = $(P_0 \cdot MP_{TDF})*TDF$,

(2) Profit Maximiiation (scale >l):

Labor's return = $(P_0 \cdot MP_{CDA}) \cdot CDA$

Vessel's return = Gross stock - $(P_0 \cdot MP_{CDA}) * CDA$

(3) Cost minimizationl labor's return for profit maximization:,

Labor's return = $(Po \cdot MP_{CDA}) \cdot CDA$

Vessel's return = $\left(\frac{MP_K}{MP_L}\right) * (POMP_{CDA}) \cdot TDF$

(4) Cost Minimizationl Labor's cost from simulator:

Labor's return = $a\left[\frac{\text{Value - Joint Expenses + Captain's Commission}}{\text{Crew}}\right]$[9]

Vessel's return = $\left(\frac{MpK}{MPL}\right)$,(Labor's return)*TDF

Corresponding estimates of (l)-(4) derived from the technology compare closely to those based on the simulator. Examination of the results suggests profit maximization for the sample of 20 vessels presented in the table. However, profit maximization, cost minimization, and possible other objectives are suggested for the entire fleet of 846 vessels. Limiting the analysis, however, is that allthough the gross returns can be approximated and some underlying objectives identified, those factors frequently having the largest effects on profit--fuel and interest--can be examined via the separability conditions in a relative,hut not absolute, sense. Aggregation and separability impose the condition that changes in input prices in one group, e.g., labor,

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[9]The simulator includes captain's commission in the vessel share.

will affect the demand for inputs in the other group, e.g., gear and electronics in capital, in a proportionate manner. However, an appropriate analysis requires additional information of the disaggregated inputs.

In summary, the cross-section estimates produce relatively useful information for fisheries analysis and decision making. However, the assumption of two aggregate inputs impose severe restrictions on the analysis. Implied is perfect substitution between the omitted inputs and those included (Parks 1971). Aggregation of outputs limits our ability to adequately determine species specific outputs and corresponding substitution possibilities. If the aggregation and necessary separability conditions do hold, the estimation and examination of output and input substitution is more easily facilitated, but limited.[10] More detailed disaggregation is desired to better examine the production technology. Nevertheless, the use of two inputs as compared to standardized effort should provide a substantially improved analytical framework over the conventional biological framework.

MULTIPLE OUTPUT TECHNOLOGY AND THE REVENUE FUNCTION

Unfortunately, the New England based or, as more commonly referred, the Northwest Atlantic groundfish industry is not a single species fishery. It is a multiple output fishery in which species are harvested jointly or together. Lack of adequate attention to the multiple output nature has created several problems for management and analysis of the fishery.

Management has typically responded to single species problems in this fishery, e.g., depressed haddock stocks or reduced landings of yellowtail

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[10] A more detailed discussion of the elasticities of demand and substitution and aggregation is presented in Diewert (1974a, 1978).

flounder. Regulations have been species specific without appropriate attention given to the incidental or joint harvests. The New England Management Council, however, must be (credited with some success; stocks appear to be stabilizing, and increased or 'constant landings appear to be sustainable. There has been some "economic" waste as harvesters have had to discard incidental harvests of regulated species jointly harvested with either unregulated or less regulated species. Best management of the fishery may have to be considered in a second best framework, but appropriate analysis need not be constrained to single species.

This section presents preliminary results of examining the technology via the revenue function. The revenue function is considered for purposes of illustration and data compatability. The primary emphasis is on the output relationships within a multiple output technology and to demonstrate concepts of duality.

Diewert (1974b) demonstrated duality between factor requirements functions and revenue functions based on the work of McFadden (1966).[11] The same assumptions of multiple outputs, single inputs, and revenue maximizing behavior are considered here. Diewert showed that given a nonzero vector of output prices (P) and, a positive input x, the revenue maximizing problem constrained by the technology $(Y^1BY)^{1/2} < x$ yields the following supply and revenue functions:[12]

$$
\begin{aligned}
Y(x;p) &= \beta^{-1} px(P^1B^{-1}P)^{-1/2}, \text{ and} \\
R(x;p) &= (P^1B^{-1}P)^{-1/2} x .
\end{aligned}
\tag{11}
$$

[11]McFadden (1966) demonstrated a duality between a restricted profit function with all inputs fixed (i.e. a revenue function) and an underlying technology.

[12]The reader is referred to Diewert (1974b) for details.

The supply equations are obtained by applying Hotelling's (1932) Lemma to the revenue function [i.e., $\frac{\partial R(x;p)}{\partial p} = (x;p)$].

The revenue function considered was

$$R^2 = \sum_{i=1}^{m} \sum_{j=1}^{m} a_{ij} p_i p_j x^2 ; \; a_{ij} = a_{ji} \; . \qquad (12)$$

Hotelling's Lemma yields

$$R_{yi} = \sum_{j=1} a_{ij} p_j x^2 \; , \qquad (13)$$

and with a suitable stochastic specification can be estimated by linear regression methods (e.g., seemingly unrelated regression). This was applied to the trawl fleet using monthly aggregations in which the input x was measured in terms of total monthly ton days fished, and yi was landings of the ith species.

Estimation was accomplished by applying seemingly unrelated regression to the eight species equations. Preliminary results are presented in Table 11; a zero entry indicated insignificant results. The results are compatible with expectations with the exception of whiting. However, whiting is not fully utilized and is often harvested at night as part of the day fishery for redfish. As indicated on the table, the supply of most species will decrease as the price of other species increases. Considerable additional analysis is required, however, before these results will be acceptable for use.

SUMMARY AND CONCLUSIONS

The empirical examination of either the single or multiple output technology in fisheries is complicated. Neither inputs nor outputs are well defined. Necessary data are often inadequate or unavailable. The multiple output technology requires substantial additional considerations. Estimation

Table 11.--Parameter estimates of revenue maximizing supply function for New England trawl fishery.

Parameter Coefficients	Species Supply Equation Estimates							
	Cod	Haddock	Yellowtail	Flounder	Redfish	Pollock	Hakes	Whiting
Price of Cod	1125.2	-108.9	-178.65	-108.9	-154.5	0	-4.9	37.85
Price of Haddock		2093.4	-76.0	-44.55	-84.7	-24.2	-20.5	608.45
Price of Yellowtail			1484.3	0	-234.85	-91.3	-26.65	640.0
Price of Flounder				803.1	0	0	-10.55	288.2
Price of Redfish					4979.4	0	-19.2	-677.25
		Symmetry Imposed						
Price of Pollock						294.9	0	57.15
Price of Hake							89.0	-52.5
Price of Whiting								8852.2

Revenue Equation: $R^2 = \sum_{i}^{m} \sum_{j}^{m} a_{ij} P_i P_j X^2$: (Diewert 1974b).

Supply Equation: $R_{yi} = \Sigma a_{ij} P_j X^2$: $([\frac{\partial R^2}{\partial P^i}] = R_{yi})$ (Hotelling's Lemma).

will likely have to be constrained to physical data since few fisheries have cost data. Desired is a specification which allows for varying returns to scale and input and output elasticities, and one in which all those same outputs are obtained by the input set. Conventional elasticities, e.g., the Allen partial for factors, may not have any relevant meaning when outputs are joint. Appropriate management of fisheries, such as the New England trawl fishery, requires appropriate consideration of the multiple output nature of the technology. One which has yet to be adequately considered.

REFERENCES

ADADIO, T., and J. E. KIRKLEY.

1981. The examination of separability and aggregation of selected fish prices: the composite commodity theorem under inexact ratio's. Unpubl. manuscr. Northeast Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Woods Hole, MA 02543.

BLACKORBY, D., D. PRIMONT, and R. R. RUSSEL.

1978. Duality, separability and functional structure: theory and empirical applications. Elsevier, New York.

BOCKSTAEL, N.

1977. A market model for New England groundfish industry. Univ. Rhode Island, Kingston, Dep. Resour. Econ., Agric. Exp. Stn. Bull. 422.

CLARK, S. A., and B. B. BROWN.

1981. Changes in biomass of finfishes and squids. Unpubl. manuscr. Northeast Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Woods Hole, MA 02543.

DENNY, M.

1974. The relationship between functional forms for the production system. Can. J. Econ. 7:21-31.

DENNY, M., and C. PINTO.

1978. An aggregate model with multi-product technologies. In M. Fuss and D. McFadden (editors), Production economics: a dual approach to theory and applications, Vol. 2, p. 249-264. North Holland Publ. Co., Amsterdam.

DIEWERT, W. E.

1973. Functional forms for profit and transformation functions. J. Econ. Theory 6: 284-316.

DIEWERT, W. E.

1974(a). Application of duality theory. In M. D. Intriligator and D. A. Kendric (editors), Frontiers of quantitative economics. North Holland pubi. co., Amsterdam.

DIEWERT, W. E.

1974(b). Function forms for revenue and factor requirements functions. Int. Econ. Rev. 15:119-130.

DIEWERT, W. E.

1976. Exact and superlative index numbers. J. Econometrics 4,2:115-146.

DIEWERT, W. E.

1978. Superlative index numbers and consistency in aggregation; Econometric 46:883-900.

HALL, R. E.

1973. The specification of technology with several kinds of output. J. Polit. Fcon. 81:878-892.

HAUSMAN, J. A.

1978. Specification tests in econometrics. Econometrica 46:1251-1272.

HOTELLING, H.

1932. Edgeworth's taxation paradox and the nature of demand and supply functions. J. Folit. Econ. 40:577-616.

KIRKLEY, J. E.

1982. A preliminary short-term analysis of the Georges Bank fishery. Unpubl. manuscr., Northeast Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Woods Hole, MA 02543.

KIRKLEY, J. E., and I. STRAND.

1981. Bionomic concepts of production in fisheries. Unpubl. manuscr., 264 p. Northeast Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Woods Hole, p4A 02543.

KIRKLEY, J. E., M. R. PENNINGTON, and B. BROWN.

1982. A short-term forecasting approach for analyzing the effects of harvesting quotas: application to the Georges Bank yellowtail flounder fishery. J. Cons., Cons. Int. Explor. Mer 40:173-175.

MCFADDEN, D.

1966. cost, revenue, and profit functions: a cursory review. Institute of Business and Economic Research, Berkeley, Calif., Working Paper 86.

MCFADDEN, D.

1978. Cost, revenue, and profit functions. In M. Fuss and D. McFadden (editors), Production economics: a dual approach to theory and applications, p. 1-110. North Holland Publ. Co., Amsterdam.

MUELLER, J. M., and P. Kurkul.

1982. Some notes on modelling the financial performance of commercial fishing fleets. Unpubl. manuscr. Northeast Reg. Off., Natl. Mar. Fish. Serv., NOAA, Gloucester, MA 01939.

MURAWSKI, S. A., A. M. LANGE, M. P. SISSENWINE, and R. K. MAYO.

1982. Definition and analysis of multispecies otter trawl fisheries off the Northeast coast of the United States. Int. Count. Explor. Sea, Demersal Fish Comm., C. M. 1981/G:62, 32 p.

PARKS, R. W.

1971. Price responsiveness of factor utilization in Swedish manufacturing, 1870-1950. Rev. Econ. Stat. 53:129-139.

THIEL, H.

1954. Linear aggregation of economic relations. North. Holland Publ. Co., Amsterdam.