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Fishing Effort: Its Testing, Specification, and Internal Structure in Fisheries Economics and Management[1]

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The concept of fishing effort is central to fisheries economics and management. However, effort is an aggregate index of inputs which can be consistently formed only under the condition on production technology of homothetic separability of inputs. This paper develops the conditions under which effort can be consistently formed. It then provides the first empirical test for effort and jointness in inputs in a fishery by estimating a multiproduct function for the New England otter trawl fleet. After not rejecting input–output separability and rejecting nonjointness in inputs, the construction of a superlative index for effort is demonstrated through estimating a translog production function. The implications of effort's internal structure for fisheries management are then considered. © 1987 Academic Press, Inc.

1. INTRODUCTION

The concept of fishing effort is central to fisheries economics and management [2, 9, 28]. Much of fisheries management is centered upon regulating the level of effort [2, 28]. Practical management requires regulating one or more components of effort, which in turn requires empirical knowledge of effort's internal structure. Effort also plays a crucial role in the specification of both static and dynamic bioeconomic models [2, 9]. In this case, effort is typically part of a multistage optimization process [1]. In the first stage, factors of production such as capital, labor, and energy are (usually implicitly) optimally and efficiently combined to form a composite input index, effort. In the second stage, effort typically becomes an input in the fishery production function. The concept of effort has yet a third fundamental role in fisheries economics and management. Estimates of effort are commonly employed in conjunction with commercial fish landings to provide a measure of relative resource abundance through the catch per unit effort index (CPUE), to estimate fishing mortality, and to track trends in industry productivity and performance over time [10].

The concept of fishing effort is thus a fundamental component of bioeconomic models, public regulation, relative resource assessment, and productivity analysis of marine fishing industries. Yet, since effort is an aggregate index of the individual factors of production, these separate components of effort can only be consistently aggregated into a composite index under a fairly restrictive condition on the production technology, homothetic separability.

Bioeconomic models not only a priori assume a composite input, effort, but in multispecies fisheries, often assume a single production process. That is, the

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presumed fishery production technology requires all inputs to harvest all outputs, which is joint-in-inputs production. If the true harvesting technology is instead nonjoint-in-inputs (output independence), then a separate production function should be specified for each species or block of species (block independence). Moreover, when modeling or regulating only a select species, bioeconomic modelers and fishery managers typically make the opposite assumption, that production is nonjoint in inputs. In this case, it is assumed that separate production processes exist, and that each process can be separately regulated without affecting production from any other process.

Fishery economics and management thus invariably maintain hypotheses upon the production technology: the existence of a consistent aggregate input, fishing effort, and if the fishery is multispecies, either nonjoint or joint production. If these conditions on production technology do not hold, then misleading results might occur in analysis and management. For example, should the true multispecies harvesting technology be joint in inputs, then a single production process exists for all the species. A bioeconomic model may instead specify nonjoint-in-inputs production (a separate production function for the species of concern) and optimize the level of effort and catch for only one of the many possible species in the fishery. The optimized results will neglect the other species and any possible species transformations in harvesting. The results will further rely upon either the tenuous allocation of joint costs to a single product or determination of harvest costs of a single output while ignoring the joint costs (which are likely to be lower) [16]. Fishery managers will then be provided misrepresentative optimum levels of total catch, total effort, and resource availability. Public regulation based on this approach is likely to be disappointing and ineffective.

Alternatively, should the harvesting technology not be homothetically separable in inputs so that an effort index cannot be properly constructed, the bioeconomic procedure will provide inconsistent results for regulation. The levels of effort and costs will be inconsistent as the catch changes: different optimal and efficient input bundles may be associated with the same level of effort, or conversely, different effort levels may be associated with the same optimal input bundle. Public regulation attempting to regulate with these results is likely to obtain unexpected results.

The purpose of this paper is to explicitly address the commonly maintained hypotheses on production technology inherent in fisheries economics and management: homothetic input separability and jointness in inputs. Rather than rely upon the questionable existence of an aggregate production technology, the study is specified at the level of the firm. This paper first formally develops the relevant concepts and provides empirical tests. The paper next demonstrates the proper empirical construction of a consistent aggregate index for effort. The internal structure of effort is then examined and the implications for public regulation noted. These concepts are empirically demonstrated through a case study of the New England otter trawl industry with firm-level panel data.

2. THE EXISTENCE OF AGGREGATES

Consider a multiproduct firm producing M products from N inputs. The set of efficient input-output combinations may be described by the firm's transformation frontier. If one output is singled out as a numeraire commodity, say Y_M, then the asymmetric transformation frontier may be defined as the maximum amount of Y_M which can be produced given the amount of the other $M-1$ outputs, Y', and N inputs X': $Y_M = F(Y_1, Y_2, \ldots, Y_{M-1}, X_1, X_2, \ldots, X_N)$.

The existence of effort (E) becomes a question of determining the conditions on the production technology under which an aggregate input index can be formed. That is, when can the transformation frontier be collapsed to: $Y_M = F(Y', E)$, where $E = f(X_1, X_2, \ldots, X_N)$ and f is a consistent aggregator function? In this case, the optimal amount of effort is first determined by solving the optimization problem $E = f(X')$ and then in the second stage of production, Y_M is optimized given Y' and E.

Separability is the relevant property of technology which allows aggregation of individual inputs into the aggregate variable fishing effort. Intuitively, the aggregate $E = f(X_1, X_2, \ldots, X_N)$ can be formed if it is possible to meaningfully rank alternative levels of effort (represented by isoquants) without knowing the levels and mixes of species harvested. Comparisons of various levels and combinations of the inputs comprising effort, i.e., comparing the isoquants, can be made independently of Y'. Thus if a fishing firm harvests more cod and less yellowtail flounder, the ranking of the input isoquants in effort is not affected, that is, the isoquants remain nested. Monotonicity still holds, since more inputs will generate at least as high a level of effort, and the isoquants radiate outward. If effort is not separable, then any attempt to construct E from X' will lead to an index for effort which varies with variations in quantities and mixes of outputs (effort isoquants twist around and might even intersect), and it is not possible to obtain a meaningful scalar measure for effort.

Several types of separability exist, but the generally relevant type for aggregation is weak separability.[2] Weak separability requires that the marginal rates of technical substitution (MRTS) between all pairs of variables in a particular group (such as effort) are independent of changes in the levels of variables not in that group (here, outputs). Strong separability is a more restrictive form of separability, and requires that the MRTS between variables of different groups be independent of the levels of variables in any other group. Strong separability implies weak separability, but the converse applies when only two subsets exist.

Separability can occur at various levels of aggregation. At the highest level, separability between inputs and outputs implies composite indices for both total catch and effort. Input-output separability implies that the marginal rates of substitution (transformation) between input (species) pairs are independent of the composition of catch (effort). In this case, F is additively separable in composite inputs and outputs: $g(Y', Y_M) - f(X') = 0$, where f and g are aggregator functions. An input–output separable harvesting technology implies that fishermen make their decisions on optimal species independently of their decisions on factor combinations. Fishermen select their species on the basis of expected relative species prices and prior knowledge subject to the technological constraints imposed by resource availability and weather conditions. Alternatively, changes in relative species prices do not affect production decisions on the optimal combinations of capital, labor, and fuel. The next relevent level of separability for the existence of

[2] Implicit separability also allows aggregation [6]. Hicks or Leontief separability further allow formation of aggregates, where prices or quantities move in fixed proportions over time; this condition is difficult to apply in cross-sectional or panel data sets.

effort is weak separability of all inputs, in which case F may be written: $Y_M = F(Y', f(X'))$.

While weak separability of the technology in all inputs is necessary and sufficient for the existence of the aggregate E, homotheticity is a necessary and sufficient condition for the validity of sequential optimization. Homotheticity insures expansion paths for the inputs comprising effort which are rays emanating from the origin. The within-group factor proportions are independent of the total level of effort. Homothetic separability of E exists if the production technology is weakly separable in X' and the aggregator function for effort, f, is linear homogenous [22]. The transformation frontier F is homothetically separable in inputs when $Y_M = F(Y', f(X'))$, where f is homogeneous degree one in X'. Homothetic separability ensures that consistent quantity and price indices exist, so that the product of the aggregate price and quantity indices of effort equals the total cost of the components of effort. Graphically, the set of all input isoquants comprising E, input expansion paths, and MRTSs between factors are fixed and independent of the particular combinations of outputs, and input expansion paths are rays from the origin with equally spaced and identically shaped isoquants. Separability between inputs and outputs and homogeneity of F is a more restrictive condition and implies the consistent formation of composite indices for both catch and effort.

Joint-in-inputs multiproduct production requires all inputs to produce all outputs, while nonjointness in inputs implies separate production functions for each output or sets of outputs. Lau shows that a transformation frontier $Y = F(Y', X')$ is nonjoint in inputs if there exist individual quasi-concave, nonnegative, monotonic functions $Y_i = f_i(X_{i1}, \ldots, X_{iN})$, $i = 1, 2, \ldots, M$, such that $F(Y', X') = \max \Sigma_i f_i(X_{i1}, \ldots, X_{iN})$ and $\Sigma_i X_{ij} = X_j$, $j = 1, \ldots, N$, and the inputs are so allocated amongst the processes that the product of no one process may be increased without decreasing the output of some one process. Production activities may therefore be consolidated, but there is not a technological trade-off between the output of one activity at the expense of another since it is possible to fully allocate the services of all inputs to each of the outputs. In contrast, a joint-in-inputs production technology implies some positive or negative external effect from one product on the production of other outputs. In the short-run, the jointness arises from either allocatable (quasi-fixed) factors or interdependent production processes, while in the long-run, only from the latter. Lau shows that input-output separability implies either jointness in inputs or individual production functions that are identical except for a scalar multiple, effectively implying only a single kind of output.

3. EMPIRICAL SPECIFICATION AND HYPOTHESIS TESTS

The general specification of the production technology and empirical tests for jointness in inputs and a consistent aggregate input index for effort are developed for an application to the New England otter trawl industry. This industry includes some of the world's most valuable fishing grounds. The most important species landed by value include cod, yellowtail and other flounders, haddock, redfish, and pollock. A typical fishing trip begins by steaming to the selected initial fishing grounds. The otter trawl net is released and dragged from the stern or side of the vessel. After some time, the catch is hauled in, released onto the deck, and the cod, haddock, and pollock gutted, sorted, and packed in ice. After return to port, proceeds from the sale of the catch are distributed among the vessel, crew, captain and trip expenses by the lay or crew share system. The particular share system formula followed varies by port, and to a lesser extent, vessel. Moss and Terkla [26] and Wilson [34] provide further details of the industry and harvesting process.

These industry characteristics provide guidelines for modeling the firm's production technology. First and foremost, a multispecies fishery implies a multiproduct technology, which should include as outputs the most important species, cod, haddock, and yellowtail and other flounders. Second, during the time period of concern, 1980–1981, outputs can largely be regarded as freely variable and endogenously determined, so that the outputs are not restricted by regulation.[3] Third, crew sizes are variable, although probably only within a range, and more so in larger vessels than smaller ones. Fourth, fishing vessels produce the vector of endogenous outputs from a vector of endogenous inputs, labor, fuel, and capital (vessel, engine, equipment, and gear).

Specification and estimation of the fishing firm's production technology by the multiproduct transformation frontier F provides one approach, but it is a difficult and limited one to empirically apply [18]. However, as is well known, the structure of technology can be examined either directly by the primal approach or indirectly by a dual formulation [8, 22]. Tests of separability, homotheticity, and joint-in-inputs production can therefore be readily applied with the dual procedure. Since both outputs and inputs are decision variables to firms, the multiproduct profit function is the preferred dual representation of technology. Moreover, the presence of well-defined auction markets, homogeneous product types, and minimal vertical and horizontal integration among a large number of firms assure exogenously determined product prices. The endogenously determined returns to labor (by the lay system) is given its proper economic and exogenous valuation by use of the opportunity cost of labor. Profits are therefore economic rather than accounting profits.

The issue of selecting a restricted or full static equilibrium specification of technology also arises. The lumpiness and long life of fishing vessels suggest a restricted model with capital as a fixed factor. Alternatively, a full static equilibrium model may be more suitable, since important used and new vessel markets, vessel leasings, and deliberate sinkings for insurance exist. Otter trawlers are also mobile and can easily switch to a gear, location, or targeted species other than those of the owners' original intentions. Perhaps most importantly, long-run investment decisions are likely to be made with expectations of a wide range of cyclical and stochastic fluctuations in resource abundance but a relatively constant spatial distribution of different species or stocks. Moreover, vessels of a certain size and design are required to fish in the stormy Northwest Atlantic and to reach fishing grounds. Squires [30] finds full static equilibrium to be the appropriate sepcification after application of Kulatilaka's [21] test.

[3] Personal communication, Dr. Guy Marchesseault, Deputy Director, New England Fishery Management Council. Some industry observers, such as Dr. James Wilson, Chair of the Statistical and Scientific Committee of the Council, feel that even by 1980, de facto regulation was virtually absent. Moreover, even if limits on the catch of each trip were to some degree binding in 1980, the use of annual data suggest that as fishermen make more frequent and shorter fishing trips, outputs are still variable, but at the cost of technical inefficiency.

The multiproduct firm's profit function provides the maximum (economic) profit as a function of product and factor prices. The profit function H is derived from the firm's maximization problem. Subject to the transformation frontier F, assume that the firm takes product prices $P = (P_1, \dots, P_M) > 0$ and input prices $W = (W_1, \dots, W_N) > 0$ as given, and attempts to adjust outputs and inputs so as to solve $\max_{YX}\{PY - WX\}$. If $\{Y^*, X^*\}$ solves this problem, then the firm's profit function is $H(P, W) = PY^* - WX^*$. For competitive firms, the technology regularity conditions imply that the profit function is finite, nonnegative, real-valued, continuous, smooth, convex in prices, twice differentiable, and bounded. H is also linear homogeneous in prices. The firm's profit-maximizing product supply and factor demand equations can be obtained directly from the profit function by Hotelling's Lemma: $D_p H(P, W) = Y^*(P, W)$ and $D_W H(P, W) = -X^*(P, W)$, where D is the vector differential operator. Properties of the supply and demand equations are inherited directly from the properties of the profit function.

The multiproduct profit function in full static equilibrium is specified with a translog functional form as a second-order Taylor's series approximation around the unit price vector by [23]:[4]

$$\ln H = A_0 + A_T T + A_{DA} \ln DA + \sum_{i \in F} A_i \ln P_i + \sum_{i \in F} \sum_{j \in F} A_{ij} \ln P_i \ln P_j$$
$$+ \sum_{i \in F} A_{iT} \ln P_i T + \sum_{i \in M} A_{iDA} \ln P_i \ln DA, \tag{1}$$

where H is economic profit (total revenue less the costs of fuel and oil, capital services, and total opportunity cost of labor), P is an 8×1 vector of 5 strictly positive ex-vessel species prices for cod, haddock, yellowtail and other flounders, and a residual, all others, and 3 input prices for labor (including captain), energy, and capital services, T is an annual dummy variable for 1981, and DA is total otter trawl fleet days absent minus the days absent of each individual vessel (representing congestion and technical externalities). The resource stock provides a technological constraint since it is external to the firm, and is captured by the 1981 dummy variable (T). For simplicity, assume that ex ante expectations are realized ex post.

The revenue and cost share equations obtained by Hotelling's Lemma are

$$\frac{\partial \ln H}{\partial \ln P_i} = \frac{P_i Y_i}{H} = A_i + A_{iT} T + A_{iDA} \ln DA + \sum_{j \in F} A_{ij} \ln P_j, \qquad \forall i \in M, N, \tag{2}$$

which are positive for outputs and negative for inputs. Without loss of generality, symmetry is imposed by $A_{ij} = A_{ji}$ for $i \neq j$ in (1) and (2). Equality between the parameters of the profit and share equations is maintained. Linear homogeneity in prices is imposed on the profit function by

$$\sum_i A_i = 1, \qquad \sum_i A_{iT} = \sum_i A_{iDA} = \sum_i A_{ij} = \sum_j A_{ij} = \sum_i \sum_j A_{ij} = 0.$$

Econometric restrictions for separate production processes for each species or nonjointness in inputs and for the existence of a consistent aggregate input index for effort may be imposed on (1) and (2) and hypothesis tests performed. The likelihood

[4] In a few instances, a species was not landed by a vessel. Since with a translog form this introduces problems with the residuals, the value 0.01 is inserted.

ratio test is used for hypothesis testing.[5] Nonjointness in inputs for all M species is tested first by the following econometric restriction at the point of approximation [12]: $A_{ij} = -A_i A_j,\ i \neq j,\ i, j \in M$.

Input–output separability implies composite indices for both catch and effort, and offers the most general test of effort's existence. If input–output separability is rejected, then a separate test for weak separability of all inputs is possible [29]. Denny and Fuss [11] state that the test for input–output separability with the translog form is an exact test for strong separability, and that failure to reject implies a Cobb-Douglas function of consistent translog aggregates for both catch and effort. The econometric restriction for input-output separability is no interaction between inputs and outputs: $A_{ij} = 0,\ i \neq j,\ i \in M,\ j \in N$.

The data set consists of 1980–1981 annual observations on 42 full-time otter trawlers with at least 85 days absent from port in each year. Home ports for the vessel and crew in each year are assigned by a plurality of days absent from port. All of the major New England ports are represented as well as a number of minor ports. The data set depicts the more productive vessels of the full-time near- and off-shore otter trawl fleet. This sector accounts for over 80% of the entire fleet's landings, and is therefore the most important for regulation and hypothesis testing. The mean sample vessel is 120 gross registered tons (GRT), has a crew size of 5, and is built in 1972. In contrast, the entire fleet's mean vessel is 70 GRT with 3 crew members. The mean sample vessel's days absent from port is 167, with a range of 85 to 249, and makes an average of 57 trips/yr of 3 days duration (with a range of 1 to 13 days). The sample vessels are typically larger and spend more time fishing than the mean fleet vessel.

All of the revenue, landings, and vessel and trip characteristics data are from the National Marine Fisheries Service (NMFS) Weighout File. Implicit ex-vessel species prices are formed by dividing total revenue by total pounds landed. Fuel and oil costs are from federal income tax returns. Most vessel acquisition prices (including hull, gear, equipment, and engine) are exact, compiled from receipts; the remainder are from federal tax returns. Both new and used vessels are included, although the majority are new vessels. Only those vessels purchased between late 1976 and 1979 are included in order to eliminate effects of vintage and structural changes in the industry. Because most of the sample consists of vessels participating in NMFS loan guarantee or capital construction fund programs, the vessels tend to be newer and more successful than most of the fleet. All data are proprietary and confidential.

The port-specific opportunity cost of labor provides an exogenous representation of returns to labor and food costs and is a Divisia index of separate opportunity costs for crew, engineer, and captain.[6] Labor cost data are from the Bureau of

[5] The likelihood ratio is the ratio (L) of the restricted to unrestricted maximum value of the likelihood function. The test statistic formed by-2 ln L has an asymptotic distribution of chi-square with degrees of freedom equal to the number of independent restrictions.

[6] Since little reliable empirical evidence is available, it is assumed only that fishermen will work in the major port towns, which are predominately industrial and blue collar. The opportunity cost of labor per crew member is a Divisia index of the opportunity costs of ordinary crew members (mean annual income of total manufacturing), the mechanic (mean annual income of maintenance mechanic, machinery), and captain (annual income 20% higher than an ordinary seaman's). These indices vary by both crew size and port. Crew members are assigned to one of five New England coastal manufacturing cities (Portland, Gloucester, Boston, New Bedford, and Providence) by geographical proximity of their home ports (as determined by a plurality of days absent from port).

Labor Statistics, U.S. Department of Labor and from comparable state agencies. Energy costs include all sales taxes, while energy prices are port-specific. The capital services price is comprised of depreciation and the opportunity cost of capital. All taxes other than sales are income taxes, and are excluded from revenue and costs because of linear homogeneity in prices. All values are deflated by the GNP implicit price index.

The profit function (1) has an additive disturbance term due to approximation error, while the revenue and cost share equations (2) have additive disturbances from errors in optimization [8]. Since the share equations sum to unity, the energy consumption equation is dropped and its parameters identified through linear homogeneity and symmetry constraints. The system (1) and (2) is estimated jointly by maximum likelihood.

3. THE EXISTENCE OF EFFORT AND JOINT PRODUCTION

Table I presents the estimated parameters of the model. The systems R^2 is 0.94, while the OLS R^2 values for the share equations range from 0.27 to 0.40, with 0.89 for the profit function.[7] The predicted share equations are positive for outputs and negative for inputs over all sample values, indicating monotonicity is satisfied. Own-price parameters with t-ratios larger than two in absolute value all display the correct algebraic signs. The restricted profit function is not convex at the point of approximation, however, and parameter estimates and tests may consequently be inconsistent with expectations of the competitive model.[8] Nevertheless, Wales [33] notes that violation of regularity conditions such as convexity need not imply the absence of an underlying optimization process, but may simply reflect the limitations of flexible functional forms to approximate the true function over the range of the data.

The hypotheses test results for nonjointness in inputs and input–output separability are now considered. A 5% level of overall significance is assumed. Nonjointness in inputs is rejected, since the chi-square statistic is 34.79, while the 5% critical value is 18.31 with 10 independent restrictions. The production technology exhibits jointness in inputs, so that separate harvesting process are not implied for the five species and all inputs are required to produce all outputs. Since the technology is in long-run equilibrium, the jointness arises from an interdependent production process. Input-output separability is not rejected, since the chi-square test statistic is 20.31, while the 5% critical value is 24.99 with 15 independent restrictions. These results indicate a Cobb-Douglas functional form of consistent translog aggregates for total catch and effort, joint-in-inputs production, and thereby provide firm-level support for the traditional bioeconomic model. A consistent fishing effort index following neoclassical production theory can now be formed.

[7]The system R^2 is calculated as $1 - \exp[2(L_1 - L_2)/N]$, where L_1 (L_2) is the maximum value of the log-likelihood when all the slope coefficients are zero (unconstrained), and N is the total number of observations [4].

[8]Since convexity is implied by the assumption of profit maximization, any violation of this condition is a serious weakness in the performance of the model.

TABLE I

Parameter Estimates of Long-Run Translog Profit Function

Exogenous variables	Cod	Haddock	Yellowtail flounder	Other flounders	All others	Capital services	Labor	Fuel[a]
	Product shares					Factor shares		
Share	−18.8674[b]	−25.7970[b]	−0.3011	36.8349[b]	15.4113[b]	−2.7941[b]	−15.6646	12.1780
Intercept	(5.7215)	(4.9191)	(3.2219)	(6.9472)	(7.7352)	(0.2030)	(12.7929)	
1981 Share	5.3492[b]	8.0111[b]	0.2321	−7.7949[b]	−1.0693	0.1245	0.0001	−4.8528
Dummy	(1.5619)	(1.4224)	(0.9104)	(1.9788)	(2.2174)	(0.0969)	(0.0001)	
Cod	−0.0065	0.0257	0.0661	−0.1313	0.0523	0.0593	0.0619	−0.1275
	(0.1011)	(0.0504)	(0.0412)	(0.1744)	(0.0768)	(0.0569)	(0.1582)	
Haddock		−0.0076	−0.0756[b]	0.0260	0.1145	0.0184	−0.0872	−0.0142
		(0.0323)	(0.0312)	(0.0841)	(0.0639)	(0.0376)	(0.0654)	
Yellowtail			0.1005[b]	−0.0144	−0.0175	−0.0123	0.0006	0.0474
Flounder			(0.0156)	(0.0768)	(0.0413)	(0.0327)	(0.0612)	
Other				1.2767[b]	0.5501[b]	−0.1757[b]	−0.7863[b]	−0.7451
Flounders				(0.2313)	(0.1541)	(0.0669)	(0.1569)	
All	(Symmetric)				0.4097[b]	−0.3023[b]	−0.6223[b]	−0.1845
Others					(0.0469)	(0.0744)	(0.1191)	
Capital						−0.1550[b]	0.3500[b]	0.2177
Services						(0.0189)	(0.0392)	
Labor							−0.3530[b]	1.4363
							(0.0360)	
Fuel								−0.6301
Fleet days	−436.5281[b]	−645.6365[b]	−17.8143	592.0388[b]	95.6826			
Absent	(123.7660)	(112.7426)	(72.3341)	(156.7265)	(177.7570)			

Profit function intercept −5.3619 (9.5457)
Profit function 1981 dummy 8.5922[b] (3.0288)
Profit function fleet days absent −840.3241[b] (218.9021)

Note. Long-run translog profit function with equality, symmetry, and linear homogeneity as maintained hypotheses. Asymptotic standard errors in parentheses.

[a]The parameters in the fuel share equation are calculated using the constraints implied by linear homogeneity and symmetry.

[b]Statistically significant at 5%.

4. FISHING EFFORT INDEX

Previous empirical studies estimating or employing fishing effort have specified ad hoc representations of technology, neglected energy, and specified restrictive functional forms such as the Cobb-Douglas.[9] Effort is typically represented as some variant of fishing time or days absent from port multiplicatively adjusted by a productivity measure, fishing power. In more recent studies, fishing power is a production function with stock proxy specifications of labor and capital (generally leading to biases). In some instances, fishing power is determined by regressing total catch (without regard to consistent aggregation) upon factors of production. Energy

[9]Cunningham and Whitmarsh, Anderson, and Clark provide bibliographies of many empirical studies, which are not presented here for the sake of brevity. These limitations apply to all stages of optimization in most bioeconomic models. A functional form is termed *flexible* if it can provide a second-order approximation to an arbitrary function. The Cobb-Douglas form imposes homogeneity, strong separability, and elasticities of substitution of one.

consumption is neglected. Relative productivities across vessel types and/or classes are then compared. However, simultaneity bias exists if effort determined in this manner is then specified as an aggregate input in a yield-effort equation.

Specification of a flexible functional form relaxes several hypotheses maintained with the linear and Cobb-Douglas forms previously employed. Moreover, Fuss [15] indicates that predictions of a dependent variable (such as fishing effort) from a flexible functional form provide superlative indices.[10] Predictions from the translog provide a superlative index equivalent to the Tornquist discrete approximation to the Divisia. These predictions can serve as instrumental variables in the multistage optimization implicit to most bioeconomic models. Simultaneous equation bias is then eliminated in subsequent stages of decision making, since fishing effort is now exogenous in these later stages. Alternatively, a superlative index is used in a revenue function or supply response framework where the level of effort is endogenously determined [24], or if effort is used to examine relative resource abundance or industry productivity.

Estimating a translog production function for effort allows construction of a consistent effort index. The translog form follows from the profit function results, which suggest a translog aggregate for effort; although not developed here, a translog consistent aggregate for total catch or revenue could also be formed. The translog production function for effort (E) specified as a second-order Taylor's series approximation to an arbitrary underlying production function about the geometric mean of the data (since all variables are scaled by their geometric means) becomes:[11]

$$\ln E = \ln B_0 + \sum_{r \in N} B_r \ln X_r + \sum_{r \in N} \sum_{S \in N} B_{rs} \ln X_r X_s + \sum_{r \in N} B_{rT} \ln X_r T, \tag{3}$$

where symmetry is imposed by $B_{rs} = B_{sr}$, $s \neq r$. T again represents a 1981 dummy variable, and X_r represents input r. The approximation error is assumed to be negligible. Assuming competitive factor markets and efficient production, differentiation of (3) with respect to the logarithms of inputs provides cost share equations [5]: $M_r = \partial \ln E / \partial \ln X_r = B_r + B_{rT} + \Sigma_{s \in N} B_{rs} \ln X_s$, $\forall r \in N$, where M_r is the relative share of input r in total cost. Constant returns to scale is required to create a consistent effort index [30]. Constant returns to scale is directly imposed by [5]: $\Sigma_{r \in N} B_r = 1$, $\Sigma_{r \in N} B_{rs} = 0$, $\forall s \in N$.

The specified variables include crew-days-fished (L), ton-days-absent (K), energy consumption (F), and a 1981 dummy variable (T).[12] The resource stock again

[10] Numerous index number formulae can be explicitly derived from particular aggregator functions. The resulting index is termed exact for that particular aggregator function. Index numbers that are exact for flexible aggregator functions are called superlative [14].

[11] Boisvert [7] demonstrates that the important characteristics of the translog production function evaluated at the geometric mean are identical to those of the exact translog production function because the Taylor expansion around zero is equivalent to scaling the data around the geometric mean. Estimation of a translog unit cost function to obtain the price of effort was not successful. However, using Fisher's weak factor reversal test and the estimated quantity index from eq. (3), an implicit Tornqvist price of effort index can be constructed.

[12] The labor and capital flow specifications are suggested by Jim Kirkley. Crew size includes captain. Ton-days-absent provides an adequate measure of the are of influence over which the gear extends, since larger vessels have the potential to fish a greater area than smaller vessels and are less constrained by inclement weather and sea conditions.

provides a technological constraint. Since the cost share equations sum to unity, the capital share equation is dropped, and the labor and energy share equations estimated,

$$\begin{aligned} M_L &= B_L + B_{LT} + B_{LL}\ln L + B_{LK}\ln K + B_{LF}\ln F, \\ M_F &= B_F + B_{FT} + B_{LF}\ln L + B_{KF}\ln K + B_{FF}\ln F. \end{aligned} \tag{4}$$

Following Berndt and Christensen, a stochastic specification is adopted which reflects errors in optimizing behavior. The equations are estimated as a system by maximum likelihood. The data are again from the National Marine Fisheries Service, federal income tax returns, and vessel acquisition receipts. Energy consumption is obtain by dividing energy costs by port-specific energy prices. Materials are an insignificant proportion of total input costs and usage.

Berndt and Christensen show that the Allen partial elasticity of substitution (AES) can be specified as: $\text{AES}_{rs} = |G_{rs}|/|G|$, where $|G|$ is the determinant of the bordered matrix whose rsth element has the form $G_{rs} = A_{rs} + M_r M_s$ and whose rth diagonal element has the form $G_{rr} = A_{rr} + M_r(M_r - 1)$. The matrix is bordered by the factor shares. Berndt and Christensen provide further details. These Hicksian elasticities represent pure substitution effects, since they are calculated for a given level (not necessarily optimal) of effort.

5. THE INTERNAL STRUCTURE OF EFFORT AND FISHERIES MANAGEMENT

Public regulation of fishing industries is extended to correct for market failure arising from an open-access resource. Like all other open-access resources, fish stocks tend to be overexploited. The resulting inefficient resource allocation and loss of economic rents are usually redressed by regulation of production, particularly management of fishing effort [2, 9, 25, 28]. Regulating the level of the effort in turn requires empirical knowledge of the internal structure of effort, that is, the relationships among the individual factors of production comprising effort. Management agencies can apply this knowledge to assess the technological constraints to firms as the latter respond to regulation and changes in market conditions. Regulatory bodies can then tailor their policies to better achieve their goals. Effective restrictions on some but not all inputs may also induce expansion of unregulated inputs, which can cause inefficient factor proportions [13, 32].

The estimated Allen elasticities of substitution can provide this information on the internal structure of effort. Moreover, the limited empirical applicability and reliability of bioeconomic models of multispecies fisheries, restrictive specification of the production technology, oversimplified and deterministic population dynamics, and limited regulatory power of regulatory agencies suggest that elasticities of factor substitution of firms may be of more reliable and immediate use to practical multispecies fisheries management than the results from aggregate or industry bioeconomic models.

Parameter estimates for the translog cost share equations appear in Table II. The estimated parameters of the capital share equation are derived from the symmetry and linear homogeneity restrictions. The bordered principal minors of the bordered Hessian matrix indicate a negative definite quadratic form and strictly convex

TABLE II
Parameter Estimates of Translog Effort Function

Exogenous variables	Labor	Energy	Capital[a]
Share intercept	0.383[b] (0.015)	0.296[b] (0.009)	0.321
1981 share dummy	−0.020 (0.021)	−0.025 (0.013)	0.045
Labor	−0.057[b] (0.010)	−0.011 (0.008)	0.068
Energy		0.077[b] (0.012)	−0.020
Capital	(Symmetric)		−0.048

Note. Asymptotic standard errors in parentheses.
[a] Parameters calculated from the symmetry and linear homogeneity constraints.
[b] t-ratios greater than 1.96.

isoquants at the geometric mean of the sample. There are no a priori restrictions on the algebraic signs of the second-order terms. The 'large' t-ratios for energy parameters suggest that fishing effort functions have been misspecified and parameter estimates biased by the omission of energy [32].

The null hypothesis that the underlying production function for effort has the simple Cobb-Douglas form is examined by a likelihood ratio test. The value of the test statistic is 31.75, while the chi-square value with 3 degrees of freedom at the 5% significance level is 7.81. The null hypothesis is decisively rejected, suggesting that previous effort functions employing a Cobb-Douglas functional form may have unnecessarily maintained restrictive hypotheses upon the structure of production (although this is an empirical question determined on a case-by-case basis).

The 1980 Allen partial elasticities of factor substitution are reported in Table III. Since the elasticities are not independent of input levels, they are calculated at the geometric mean of the data set. Standard errors are not presented, since each elasticity is a nonlinear function of all the first and second partial derivatives of the production function. The Allen partial elasticities of substitution indicate that all three inputs, capital, labor, and energy, are substitutes and are generally elastic. The inelastic AES between capital and labor indicates limited substitution possibilities, but otherwise the substitution possibilities are elastic between labor and energy and capital and energy. The own-price factor demand elasticities for all three inputs are negative as expected, and are all elastic, especially capital and labor.

TABLE III
1980 Own-Price Elasticities of Factor Demand and Allen Partial Elasticities of Substitution

Item	Labor	Capital	Energy
Labor	−1.643	0.726	1.946
Capital		−2.821	2.125
Energy			−4.033

The generally elastic substitution possibilities between capital, energy, and labor suggest a rather series potential for expansion of unregulated inputs. Inefficient factor proportions are then possible, and management might need to regulate more than one input. For example, capital can be regulated to reduce the level of effort in the industry, such as the current policy of limiting mesh size or restricting ultra free entry or market contestability through limiting vessel numbers. Reducing effort may reduce open-access social inefficiency, but might also induce inefficient factor proportions of firms by unanticipated expansions in crew size or energy consumption if fishermen substitute the unregulated inputs for the regulated input, capital. Strand *et al.* [32] present the only other study which empirically estimates measures of multifactor substitution with a functional form that places no prior restrictions on elasticities of substitution, the transcendental. They measure similar multi-factor substitution possibilities in the Atlantic surf clam industry. Through observation, other researchers indicate similar findings by reporting unanticipated factor substitution in many fisheries [20, 27]. Potential gains in social efficiency may then be dissipated through increases in costs [25].

The problem of unanticipated factor substitution and economic inefficiency is unimportant if factor complementarity or inelastic factor substitution possibilities exist. Otherwise, public regulation ostensibly might regulate all the individual inputs comprising effort. However, social and cultural factors and regulatory costs (and in New England, New Bedford union resistance) are likely to make this management approach difficult to implement. Moreover, Anderson's [3] recent theoretical analysis demonstrates that in some cases there are potential rent gains to regulating some but not all factors even if there is factor substitution. Practical fishery management in New England and other fisheries might therefore want to regulate the most easily monitored and enforced input; the current New England plan of managing mesh size is certainly consistent with this regulatory approach.

Regulatory programs limiting the number of vessels often experience not only unanticipated factor substitution of unregulated inputs, but increases in the quantity of capital [2, 20, 25, 27, 28, 32]. In this manner, fishermen attempt to capture any increases in rents arising from regulation. The reported elastic own-price demand for capital indicates that if a limited access program were to be implemented in New England, that similar to other fisheries, an increase in productive capacity is likely to be experienced. The elastic own-price demand for capital also suggests that the problem of capital expansion could be potentially serious. Any limited entry program implemented in New England may want to consider limitations on capital other than simply the number of vessels.

The internal structure of fishing effort also provides technological constraints important for industrial policies. The general elastic capital-labor-energy substitutability suggests that maintenance of U.S. energy prices below world levels encourages inefficient input usage and possibly socially suboptimal pressures on the resource through inducing increases in the level of fishing effort. Policies designed to reduce energy consumption by promoting substitution with other inputs can be counterproductive. Moreover, industry relief through financial assistance programs which lower the real interest rate to fishermen may increase the level of fishing effort beyond the social optimum. Similarly, policies designed to increase industry productivity through capital expansion may increase usage of all inputs and expand pressure on the resource stock. For example, Karpoff [19] reports that government financial assistance to purchase fishing assets such as a limited entry license or capital can induce expansion. Alternatively, policies designed to lessen pressures on energy markets, such as investment tax credits, may encourage a fleet expansion which places socially suboptimal pressures on the resource stock that would remain after problems in energy markets have abated. The industry is also likely to retain surplus labor with stagnant real wages and high unemployment in the old and industrially torpid New England port cities due to the elastic labor demand with respect to the opportunity cost of labor. Finally, the fuel price shocks and subsequent high interest rates of recent years may have also induced substantial factor substitution.

CONCLUSIONS

Although production technology plays a pivotal role in fisheries economics and management, several important hypotheses are traditionally maintained upon its structure. Fishing effort is implicitly specified to be a consistent composite index of the individual factors of production formed as an intermediate input in a multistage decision making process. The production technology in multispecies fishing industries is also traditionally assumed to be joint in inputs in bioeconomic models, while fishery managers often assume that individual production processes exist. This paper rigorously addresses these issues and provides a means by which to empirically test the structure of production for the existence of fishing effort and joint-in-inputs production. This paper also demonstrates the theoretically proper manner by which to construct a consistent effort index which can then be used in bioeconomic models, industry performance studies of relative resource abundance and productivity, and public regulation of production. These concepts are developed in an empirical study of the New England otter trawl industry.

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