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Public regulation and the structure of production in multiproduct industries: an application to the New England otter trawl industry

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This article considers the problem of managing multispecies fishing industries as one of regulating the production of individual multiproduct firms. The multispecies New England otter trawl industry is examined within this framework. Empirical results derived from estimating a multiproduct profit function indicate that management consistent with the structures of multiproduct production and costs would directly regulate inputs. Little support is provided for applying the traditional bioeconomic model to the fishery studied.

1. Introduction

■ Public regulation of multispecies fishing industries is imposed to correct for market failure arising from an open-access resource. Like other open-access resources, fish stocks tend to be overexploited. The resulting inefficient resource allocation and loss of economic rents are usually redressed by regulating production. These attempts at public regulation, however, are likely to be disappointing because of a failure to recognize the management problem as one of regulating the production of individual multiproduct firms. Public regulation instead focuses at the industry level and either attempts to manage an aggregate input, fishing effort, and total industry catch, or targets individual species and inputs while neglecting their technological and cost interrelationships. The formulation of public regulation of production in multispecies fishing industries thus faces a conceptual problem, and such policies should be based on sound empirical knowledge of the firm-level structure of production and costs. Regulatory agencies can apply this knowledge to assess the technological and cost conditions facing individual firms, and the agencies can thereby tailor their policies better to achieve their goals.

The New England otter trawl industry[1] provides an example of a multispecies fishing industry in which failure to recognize the management task as one of regulating the pro-

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[1] Otter trawling involves dragging a net at the stern or side of a vessel. Large otter boards and floats on the top mouth and weights on the bottom mouth keep the net open. After a period of time, the net is hauled in and its catch released onto the deck.

duction of multiproduct firms contributed to ineffective regulation. The Magnuson Fisheries Conservation and Management Act (hereafter the Magnuson Act) of 1976 charged eight regional fishery management councils with public regulation of their regional fishing industries. The New England Fishery Management Council introduced a management plan in 1977 for the three most important species in its otter trawl fishery: cod, haddock, and yellowtail flounder. Although the plan evolved over time, it principally consisted of catch quotas for individual species and closures of particular fishing grounds. The plan placed possibly undue emphasis upon output regulation and relied upon controls that were often too intricate to implement and to enforce consistently. Most importantly, individual species were regulated as if each was harvested in a separate production process with no technological and cost interrelationships. Quotas were continually shortened in time (from annual to quarterly to trip) to prevent the entire quota from being harvested at the start of each time period. These limitations reduced profits, increased discards of fish caught beyond the quota level, and led to unexpected substitution of species in harvesting.

Thus, public regulation of this multispecies fishery failed, in part, because of an imperfect understanding of multiproduct production at the level of the firm and limited empirical information on the firm's transformation and substitution possibilities. The result was increasing political resentment and widespread evasion of the regulations. By 1980 an important reduction of the regulatory burden was experienced, and by 1981 enforcement was certainly at a minimum as preparation for the Interim Plan began.[2]

This study addresses this relationship between public regulation of inputs and outputs and the structure of multiproduct production in the multispecies New Enland otter trawl industry. Particular attention is given to the complexities of multiproduct technology to be addressed by regulation. Moreover, although the multiproduct cost structure is usually more important to regulation of market structure, knowledge of firms' costs does allow regulation of production to promote efficient production and multiproduct industry structure, and is developed in this study. Implications for the specification of bioeconomic models of fisheries are also provided. Since regulating the production of multiproduct firms is important to public regulation of industries other than fishing, the general procedure developed in this study has broad application.

The next section provides a background to the industry. Section 3 introduces the empirical model and describes the data. Section 4 examines the formal relationship between regulation of inputs and outputs and the structures of multiproduct production and costs. Section 5 reports the empirical results and considers the implications for public regulation, and the last section contains concluding remarks.

2. The industry

■ The New England otter trawl industry exploits some of the world's most valuable fishing grounds. Few firms are horizontally integrated to include more than one vessel, and individual owners operate most vessels. Vertical integration between shore-side processors and vessels also remains limited. The most important species harvested (in order of value) are cod, yellowtail and other flounders, haddock, redfish, and pollock. Cod is widely distributed over all the fishing grounds, and cod and haddock have traditionally formed the mainstay of the industry.

A number of ports dot the coast, each of which has developed a singular reputation. Rockland and Portland in Maine and Gloucester in Massachusetts are generally recognized

[2] Personal communication, Dr. Guy Marchesseault, Deputy Executive Director, New England Fishery Management Council. Some industry observers, such as Dr. James Wilson, Chair of the Statistical and Scientific Committee of the Council, believe that even by 1980, regulation was in fact virtually absent. The Interim Plan includes limited area closures for spawning and mesh size limitations, but not quotas.

as cod, haddock, pollock, and redfish ports; Boston as a cod and haddock port; Provincetown and New Bedford in Massachusetts as flounder ports; and Port Judith in Rhode Island as a port of underutilized species such as scup and butterfish. Distances and access to fishing grounds also vary by port and contribute toward port specializations. Rockland and Portland vessels tend to fish in the Gulf of Maine, New Bedford and Provincetown vessels off Georges Bank, Gloucester trawlers off both, and Point Judith trawlers in southern New England and Georges Bank waters.

Fishermen of all ports are free to land their harvests at any port offering the highest price. This option, however, must be balanced against the additional travel time, market transaction costs, and personal and financial relationships existing between many fishermen and fish buyers. New Bedford and Boston contain important auction markets for landings (Wilson, 1980).

The vessel is one of the most important elements in the production process. Vessel size reflects fishing capacity and constrains the areas and seasons of operation. Smaller vessels below approximately 30 gross registered tons (GRT) are generally limited to inshore day trips during favorable seasons. Vessels of about 45 to 60 GRT make either single or multiday trips in nearshore waters, depending upon the season and expected prices and resource abundance. Vessels over 60 GRT are less subject to seasonality, fish year round, can fish offshore, and make multiday trips.

Crew size can vary, although as in all production processes, only within a range. Vessels of certain sizes and designs have minimum crew requirements. Institutional factors such as tradition, family ties, ethnicity, or the New Bedford union (Teamsters Local #59) can make changes in crew size difficult. Nevertheless, crew sizes can, and do, change according to economic conditions (Moss and Terkla, 1985).

A typical fishing trip might consist of steaming to the desired initial fishing ground, where the otter trawl net is released and towed for several hours. The harvest is then hauled in, and the fish sorted, gutted, and packed in ice. Captains can alter the level and composition of catch by selection of net type, mesh size, speed and depth of tow, fishing grounds, and so forth. Changes in species composition occur with changes in expected relative output and factor prices, biological abundance, and seasonality. After return to port, proceeds from sale of the catch are apportioned among vessel, crew, and trip expenses by the lay system. In this system various trip or operating costs, such as fuel, food, and ice, are first subtracted from the gross revenue, and this net trip revenue is then divided among captain, crew, and owner of the vessel. The particular formula for allocating shares varies by port, and to a lesser extent, by vessel.

3. Empirical specification

■ Bioeconomic models traditionally form the conceptual basis for regulation of multispecies fishing industries. The basic model consists of a single aggregate input, fishing effort, and either an aggregate output, total catch, or a separate production process and model for each species (Clark and Munro, 1980). Simplified and deterministic population dynamics are specified, which relate gross weight of the biomass to growth, mortality, and environmental parameters. The aggregate production function relates total industry catch to industry effort and resource abundance in a restrictive functional form, almost invariably the Cobb-Douglas structure. The basic static model then combines the population dynamics and fishery production function to give steady-state optimal levels of catch, effort, and abundance. Regulatory agencies compare the unregulated, free-entry levels to target solutions, and manage the control variable, effort, accordingly. Capital-theoretic or dynamic models further provide optimal time paths of catch, effort, and abundance.

The theory of duality at the level of the firm offers an attractive alternative to the bioeconomic approach. While the dual framework does not focus on steady-state levels of the variables, it offers the more immediate and detailed knowledge of the individual firm's technology and costs required for practical regulation. The approach obviates the conceptual problem of managing industry abstractions, catch and effort, and instead offers specific empirical knowledge to regulate the individual inputs and outputs comprising these variables. Public regulation can then be consistent with the technological and cost conditions facing firms. The procedure also accords better with the limited regulatory power and uncertain biological information often encountered by management agencies, and it does not rely upon the questionable existence of an aggregate input and an aggregate production function.

The brief survey of the New England otter trawl industry suggests a number of guidelines for modelling the firm's production technology by the dual approach. First and foremost, the presence of multiple species implies a multiproduct technology, which should include as outputs the most important species: cod, haddock, and yellowtail and other flounders. Second, during 1980 and 1981, the time period of concern, outputs can largely be considered as freely variable and endogenously determined.[3] Third, the large number of vessels in the industry, homogeneous products, and minimal vertical and horizontal integration assure exogenously determined output prices. Fourth, although the labor payments are based on a share system, the proper economic valuation is the opportunity cost of labor.[4] This approach also provides an exogenous wage rate for the model. Fifth, crew sizes are variable, although probably only within a somewhat restricted range, and more variable in larger vessels than in smaller ones. Sixth, along with labor, fuel and capital (in the form of the vessel, gear, and equipment) are organized to produce the multiple products.

Fishing firms may thus be regarded as multiproduct firms producing a vector of endogenous outputs from a vector of endogenous inputs. This suggests that the multiproduct profit function is the appropriate dual representation of the firm's production technology. Finally, the area in which a firm operated can affect the production technology through port effects on prices and the spatial distribution of fish stocks. To account for these effects, three area dummy variables are included: one each for New Bedford, Rhode Island, and Maine. The intercept includes Gloucester, Boston, Provincetown, and the remaining Massachusetts ports other than New Bedford.

A choice must also be made between using a restricted or a full static equilibrium representation of technology. 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 used and new vessel markets, vessel leasings, and deliberate vessel sinkings for insurance are important aspects of the capital market. Moreover, otter trawlers are mobile and can easily switch gear, location, and targeted species. Squires (forthcoming) finds full static equilibrium to be the appropriate specification after application of Kulatilaka's (1985) parametric test.

I therefore use a full static equilibrium multiproduct profit function with the results conditional on existing stock levels of the species. A translog profit function is specified as a second-order Taylor series approximation:

$$\ln \Pi = A_0 + A_T T + \sum_{k\in 3} A_k R_k + \sum_{i\in F} A_i \ln P_i + \sum_{i\in F}\sum_{j\in F} A_{ij} \ln P_i \ln P_j + \sum_{i\in F} A_{iT} T \ln P_i + \sum_{i\in F}\sum_{k\in 3} A_{ik} R_k \ln P_i, \quad (1)$$

[3] Even if limits on the catch of each trip were to some degree binding in 1980, the use of annual data suggests that as fishermen make more frequent and shorter trips, outputs are still variable, but at the cost of technical inefficiency. See also footnote 2.

[4] Clark and Munro (1980) adopt the opportunity-cost approach in their model of fisheries production. This procedure is also commonly followed in studies of agriculture in which family labor is involved (Lopez, 1984). The approach is also fundamental to deriving capital service prices and the concept of normal profit.

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 $F \times l$ vector of strictly positive species prices (M of them) and input prices (N of them), T is an annual dummy variable for 1981, and R_k is the kth of the three area dummy variables.

I obtain the revenue and cost share equations by applying Hotelling's lemma:

$$\frac{\partial \ln H}{\partial \ln P_i} = \frac{P_i Y_i}{H} = A_i + A_{iT} T + \sum_{k \in 3} A_{ik} R_k + \sum_{j \in F} A_{ij} \ln P_j, \qquad \forall i \in F, \tag{2}$$

where Y_i is the quantity of the ith input or output. These shares 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: $\sum_{i \in F} A_i = 1$, $\sum_{i \in F} A_{iT} = \sum_{i \in F} A_{ik} = \sum_{i \in F} A_{ij} = \sum_{j \in F} A_{ij} = \sum_{i \in F} \sum_{j \in F} A_{ij} = 0$.

The most disaggregated version of (1) and (2) specifies five outputs: cod, haddock, yellowtail flounder, other flounders, and a residual (all others) and three inputs: capital services, labor (including the captain), and energy (fuel and oil) consumption. Resource abundance is specified as a technological constraint since it is beyond the control of any individual firm but nevertheless affects the production environment within which the firm operates. Changes in resource abundance may then be viewed as shifts in the production technology that relates the generation of outputs from inputs (McFadden, 1978). These changes are represented by the 1981 dummy variable.

□ **The data.** The balanced panel data set consists of annual observations for 2 years, 1980–1981, on 42 full-time otter trawlers, each of which was absent from port for at least 85 days 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 ones such as Newport, Rhode Island, and Sandwich and Plymouth, Massachusetts.

The data set includes the more productive vessels of the full-time near- and offshore otter trawl fleet. This sector accounts for over 80% of the entire fleet's landings and is therefore the most important for regulation. The mean sample vessel is 120 GRT, has a crew size of 5, and was 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 the vessel makes an average of 57 trips per year 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 Weighout File. Implicit exvessel 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 and 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, to eliminate effects of vintage and structural changes in the industry that resulted from the Magnuson Act. Any new equipment and gear purchased in 1980 for use in 1981 are included. Because most of the sample consists of vessels participating in National Maritime Fisheries Service loan guarantee or capital construction fund programs, the vessels tend to be newer and more successful than most of the fleet. Most data are confidential.

The opportunity cost of labor per crew member is an exogenous measure of returns to labor and food costs per person. Since little reliable empirical evidence is available on fishermen's alternative employment possibilities, it is assumed only that fishermen will work in the major port towns, which are predominantly industrial and blue collar. The opportunity cost of labor per crew member is a Divisia index of the opportunity costs of the crew (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 indexes vary by both crew size and port. To derive the index, crew members are assigned to one of five New England coastal manufacturing cities (Portland, Gloucester, Boston, New Bedford, and Providence) on the basis of the geographical proximity of their home ports. Labor cost data are from the U.S. Department of Labor, Bureau of Labor Statistics, and from comparable state agencies.

Energy prices are cash prices for number two diesel fuel from marine fuel docks of the major ports, and vessels from minor ports are assumed to face the energy prices of the closest major ports. Energy costs include sales taxes. The capital services price comprises the opportunity cost of capital and depreciation. All values are deflated by the GNP implicit price index.

The profit function (1) has an additive disturbance term owing to approximation error, while the revenue and cost share equations (2) have additive disturbances from errors in optimization (Burgess, 1975). Disturbances are also likely to arise from the stochastic nature of fishing. Since the share equations sum to unity, the energy consumption equation is omitted and its parameters are identified through the linear homogeneity and symmetry constraints. I estimate the system (1) and (2) jointly by maximum likelihood.

4. Public regulation and the structure of production

■ The structure of production has several implications for efforts to regulate multiproduct production by managing the levels of inputs and outputs. The production constraints imposed can be either primal, such as output quotas, or dual, such as an output tax or a fee on the number of production units or firms in an industry. The two types of constraint are equivalent at the level of formal analysis in a static, full-information, deterministic framework (Weitzman, 1974).

□ **Aggregation.** The appropriate level of aggregation of inputs and outputs carries with it important implications for public regulation. At the highest level of aggregation, only a single composite output and input exist. Multispecies bioeconomic models traditionally maintain this level of aggregation, where the composite input is called fishing effort. This level of aggregation requires separability between inputs and outputs, and it implies that the marginal rates of substitution between factor pairs are independent of the composition of catch, while the marginal rates of transformation between species pairs are independent of the composition of inputs. Conceptually, only the levels of the catch and effort require regulation, and regulation of the input (species) mix does not adversely affect the optimal product (factor) combinations. Considerable flexibility is thus afforded to regulators. The econometric restriction needed to test for input-output separability is that there is no interaction between inputs and outputs: $A_{ij} = 0$, $i \neq j$, $i \in M$, $j \in N$. The likelihood ratio test is employed to test this and all other restrictions.[5]

Lower levels of aggregation, and thus separability, allow more precise targeting of regulations. Output (input) separability implies a single product (factor) and independence of optimal product (factor) combinations from the composition of inputs (outputs). Weak separability among only a subset of inputs or outputs may also exist. It implies that the marginal rates of substitution or transformation between variables of a subset are independent

[5] The likelihood ratio L is the ratio of the restricted to the unrestricted maximum value of the likelihood function. The test statistic formed by $-2 \ln L$ is asymptotically distributed as a chi-square with degrees of freedom equal to the number of independent restrictions. A significance level of 1% is adopted.

of the mix of other variables. This allows separate regulation of the subset's components without affecting the optimal mixes of the remaining outputs and inputs. Tests for weak separability are applied to the two most economically important species groupings, cod and haddock to form the aggregate roundfish, and yellowtail and other flounders to form flatfish. Weak separability at the point of approximation of some partition I of outputs requires that $A_j A_{ik} - A_i A_{jk} = 0,\ i \neq j \neq k,\ \forall i, j \in I,\ k \notin I$ (Denny and Fuss, 1977).

If the profit function is weakly separable over a subset of its outputs, such as cod and haddock, the firm's optimization procedure can be treated as a two-stage process. The optimal combination of outputs within the subgroup is selected first, followed by the choice of the appropriate levels of the aggregate for this subgroup and of the other outputs and inputs. Homotheticity of the profit function in this product group then allows consistent aggregation within the subgroup so that the product of the price and quantity indexes for it equals its total value. With the translog form, the restriction for homotheticity of a subset I of outputs is: $\sum_{\forall j \in I} A_{ij} = 0,\ \forall i \in I$.

The two-stage optimization procedure may be applied by using the translog unit revenue function as a price aggregator function (Fuss, 1977). The translog price index provides a Tornquist discrete approximation to the Divisia index and is written as:

$$\ln P_I = B_0 + \sum_{a \in I} B_{aT} T \ln P_a + \sum_{a \in I} \sum_{k \in 3} B_{ak} R_k \ln P_a + \sum_{a \in I} \sum_{b \in I} B_{ab} \ln P_a \ln P_b, \qquad (3)$$

where linear homogeneity and symmetry are imposed. Since P_I is an unobservable variable, equation (3) cannot be estimated directly. Instead, a set of revenue share equations is derived by using Hotelling's lemma and estimated by maximum likelihood:

$$U_a = B_a + B_{aT} + \sum_{k \in 3} B_{ak} R_k + \sum_{b \in I} B_{ab} \ln P_b, \qquad \forall a \in I, \qquad (4)$$

where U_a is the revenue share of the ath output in the set I for which the aggregate has been formed. Estimated parameter values from (4) are then inserted in (3) to obtain an estimate of $\ln P_I$, which is then used in the estimation of the profit function (1) and share equations (2) (Fuss, 1977).

□ **Jointness.** Public regulation of production in multiproduct industries is afforded additional precision and flexibility if there exist separate production processes for outputs, that is, if production is nonjoint in inputs. The output of any single process then depends only on the inputs used in that process and not on the level of inputs or output(s) in any other production process. Each production process can be separately regulated without affecting production of the other processes because there are no technological or cost tradeoffs between the output of one activity and that of another. The existence of a production process for each output i is tested with the translog form at the point of approximation by $A_{ij} = -A_i A_j,\ i \neq j,\ i, j \in M$ (Denny and Pinto, 1978).

The results of this test for nonjointness in inputs will also have important implications for the specification of the fishery production function in multispecies bioeconomic models. These models traditionally assume either nonjoint production (a separate production function for each species) or input-output separability with joint production (a single output and input, and all inputs used to produce all outputs).

□ **Transformation and substitution possibilities.** By restricting individual inputs and outputs, public regulation may induce inefficiency and unexpected results. Input regulation can limit the use of certain inputs in production or it can limit entry into an industry. Effective regulation of inputs may then induce unanticipated expansion of unregulated inputs and cause inefficient production (DeVany *et al.*, 1982). Market contestability or free entry might also be reduced if regulation limits the mobility of capital and the recoverability of fixed costs. Output levels can similarly be constrained, and thus lead to unanticipated transformations and inefficiency.

The Marshallian elasticities of factor demand and product supply obtained from the profit function indicate substitute or complementary relationships among inputs and outputs and therefore the possibility of unanticipated expansions or contractions of factors and products when regulation is imposed. These elasticities include both expansion effects and pure substitution effects. With the translog form, the elasticities' formulas are: $V_{ii} = (A_{ii} + U_i^2 - U_i)/U_i \ \forall i \in M, N$ and $V_{ij} = (A_{ij} + U_i U_j)/U_i, \forall i, j \in M, N$, where U_i is the ith fitted share at the sample arithmetic mean, and $U_i > 0$ for outputs and $U_i < 0$ for inputs.

When the two-stage optimization procedure is applied to a group of outputs, two elasticities can be computed for any two outputs a and b (e.g., cod and haddock) aggregated into I (roundfish). The gross price elasticity E^*_{ab} is conditional on the fixed aggregate I, while the net price elasticity E_{ab} allows the aggregate I to be endogenous. Outputs could be gross complements in the first stage, yet net substitutes in the second. The relationship between the gross and net price elasticities is $E_{ab} = E^*_{ab} + U_b V_{II}$, $a, b \in I$, where U_b is the fitted revenue share of output b in the aggregator function for I (equation 4) and V_{II} is the Marshallian own-price elasticity of I (Fuss, 1977).

□ **Multiproduct cost structure.** The firm's structure of costs provides further information that is useful for public regulation that aims to promote efficient production and multiproduct industry structure. The measure of multiproduct (ray) returns to scale offers an indication of the efficiency of the scale of production for the existing product mix and level of resource abundance. Regulation of production can alter the overall scale of production by affecting the levels and mixes of outputs and inputs and, in natural resource industries, by altering the mix and level of resource availability. The degree of overall scale economies at the point of approximation for the translog form is calculated by $S_M = \sum_{j \in N} U_j / \sum_{i \in M} U_i$ (Weaver, 1983).

Product-specific economies of scale measure the change in costs through variations in the output of one product while holding the quantities of other products constant. These measures can indicate whether public regulation might encourage expansion in the scale of production of individual products and whether specialized firms producing only a single product are likely. They can also alert managers to a natural resource that may suffer excessive depletion as firms expand their production to enjoy cost savings. Although product-specific economies of scale cannot be directly measured by the translog profit function, sufficient information is obtained by examining the structure of incremental marginal costs (Baumol, Panzar, and Willig, 1982). The measure for product i at the point of approximation is $S_i = (A_{ii} + A_i^2 - A_i)^{-1}$. An estimated value less (greater) than zero implies decreasing (increasing) product-specific returns to scale for product i.

Although economies may be associated with the level of output, economies may also be associated with the composition of output. Public regulatory agencies can use knowledge about such economies to assess the relative efficiencies of different product combinations and to design their policies accordingly. For example, if joint harvesting of several fish species results in cost savings, then regulating one of the species might increase harvesting costs of the other species. Economies of scope measure these effects of joint production upon costs in which production that jointly uses inputs costs less than independent production of several products. The profit function cannot directly measure overall economies of scope, but weak cost complementarity between product pairs provides a sufficient condition for such economies to exist in the long run (Baumol, Panzar, and Willig, 1982). The condition for pairwise weak cost complementarity at the point of approximation provides a nonstatistical test of economies of scope, and with the translog form, this condition is $S_{ij} = (A_{ij} + A_i A_j)^{-1} < 0, i \neq j, i, j \in M$.[6]

5. Empirical results and implications for public policy

■ The values of the estimated parameters of the disaggregated model are not reported, but they are available from the author upon request. The generalized R^2 is .99, and is calculated as $1 - \exp[2(L_1 - L_2)/N]$, where $L_1(L_2)$ is the maximum value of the log-likelihood function when all slope coefficients are zero (unconstrained), and N is the total number of observations. The ordinary least squares R^2's of the individual share equations range from .30 to .53, and the ordinary least squares R^2 of the profit function is .88. The predicted share equations are positive (negative) for outputs (inputs) over all observations, which indicates that monotonicity is satisfied.

The profit function is not convex at 81% of the sample points. Parameter estimates and tests may be inconsistent with expectations of the competitive model, although this is not a statistical test. Convexity is implied by the assumption of profit maximization, but a test of convexity cannot be interpreted as a strict test of this assumption because convexity may be violated for a number of other reasons. For example, Wales (1977) shows that estimates of a flexible functional form may violate convexity even if the data come from a well-behaved technology. Inconsistent aggregation, such as the linear aggregation over 50 different, minor species groups to form the all others species aggregate, can also contribute to the failure to obtain convexity. Finally, although eliminating statistically insignificant parameters from the model can lead to convexity, one would be imposing an unknown structure upon the results.

The translog form was selected as in Lopez (1985). A problem arose for 16 of the 420 total output observations because a zero output was encountered, and, of course, the translog form is not well defined when an output level is zero. The Box-Cox transformation ostensibly provides one solution to this problem, but this form imposes input-output separability and additive separability for linear profit terms (Lopez, 1985) and assumes nonnormal disturbances before transformation. The recently proposed procedure of Lee and Pitt (1986), using virtual prices, is not yet computationally feasible with the number of variables of this study. The solution adopted here was to estimate the function at an arbitrarily small level of output prices, .01. Robustness of the estimated results was assessed by reestimating the model with a range of small product price levels, .10 and .001 and by including a dummy variable when a zero output appears. The log-likelihood value changes by .04% with the dummy variable approach, by 2.6% with .10 price values, and by .6% with .001 price values. Parameter estimates are generally robust except for the .10 case, in which some of the haddock and yellowtail flounder values (where all the zero outputs occur) are most affected. The overall qualitative results of the model are likely to be robust to the value selected to represent zero output prices.

The empirical results provide only limited support for the traditional bioeconomic model. A detailed report of the hypothesis tests is given in the Appendix. I find evidence for jointness in inputs or a single production process, but support is not provided for the existence of a composite index of outputs (total catch) and inputs (fishing effort) or for a Cobb-Douglas functional form. Weak separability is found for roundfish (cod and haddock) and flatfish (yellowtail and other flounders), but a consistent translog aggregate can be formed by the two-stage optimization procedure only for roundfish. Fishermen thus separately

[6] Lopez (1984) and Sakai (1974) show that $\partial^2 C/\partial Y_i \partial Y_j = [\partial^2 H/\partial P_i \partial P_j]^{-1}$ and $\partial^2 C/\partial Y_i^2 = [\partial^2 H/\partial P_i^2]^{-1}$ $i, j \in M$. By Hotelling's lemma and marginal cost pricing, $[\partial^2 H/\partial P_i \partial P_j]^{-1} = [\partial Y_i/\partial(\partial C/\partial Y_j)]^{-1}$, which provides the definition of weak cost complementarity between products i and j. The extension to incremental marginal costs is straightforward.

optimize revenue and species mix for roundfish and flatfish before beginning the general profit maximization problem.

The profit function is reestimated with a translog aggregate for roundfish in the form of equation (3). Table 1 provides the parameter estimates for the translog roundfish unit revenue function. Table 2 reports the profit function's parameter estimates.

The estimated structure of production does not provide encouragement for a program of straightforward, simple regulation of production. A multiproduct production technology without separability between inputs and outputs precludes simply regulating the levels of total catch and fishing effort. Instead, individual outputs or inputs must be regulated. Optimal output and input mixes can be adversely affected by regulatory constraints because input and output allocation decisions are not independent. The separability of roundfish and flatfish does allow regulation of their individual components without distorting the optimal output and input proportions. Joint-in-inputs production further narrows the regulatory options by precluding separate regulation of individual harvesting processes: the problem of technological and cost interdependence with joint production must be addressed.

□ **Technological interdependence.** The technological tradeoffs among inputs and outputs with joint harvesting are measured by the Marshallian elasticities reported in Table 3.[7] Not

TABLE 1 Parameter Estimates of Roundfish Unit Revenue Function*

Prices and Other Exogenous Variables	Revenue Shares: Cod	Revenue Shares: Haddock[a]
Intercept	.631	.369
	(.039)	(.039)
1981 Dummy	−.019	.019
	(.040)	(.040)
New Bedford Dummy	.198	−.198
	(.051)	(.051)
Rhode Island Dummy	.291	−.291
	(.057)	(.057)
Maine Dummy	.171	−.171
	(.055)	(.055)
Cod Price	.057	−.057
	(.022)	(.022)
Haddock Price	−.057	.057
	(.022)	(.022)
R^2	.58	
S.E.	.173	

* Standard errors in parentheses. Translog unit revenue function with symmetry and linear homogeneity directly imposed.

[a] Parameter estimates are derived from the constraints for linear homogeneity and symmetry. Linearized standard errors in parentheses.

[7] Again, these elasticities include both expansion and transformation effects. Standard errors of the elasticities are computed as square roots of var $(A_{ij})/U_i^2$ and var $(A_{ij})/U_j^2$. The fitted values of the shares are treated as nonstochastic.

shown there are the net cross-price elasticities for cod and haddock, the components of roundfish, which are .41 and .66, indicating inelastic net complementarity. The results in Table 3 indicate that the landings levels for different species can be reduced by regulating only a limited number of species because of the widespread Marshallian complementarity among outputs. Expansions in the overall levels of landings of unregulated species are not a serious problem since only limited Marshallian species substitution exists.

Substitution of unregulated species for the regulated species may still occur although the absolute level of each species declines. Pressures that are greater than anticipated may then be placed upon the resource stock, catches of even regulated species could surpass the established quotas, and inefficient product proportions are still possible. Regulators might respond by additional management measures, which increase the complexity of regulations and create further uncertainty in the production environment. Allen elasticities of product transformation measuring the pure transformation possibilities are presented in Table 4.[8]

TABLE 2 **Parameter Estimates of Translog Profit Function***

Prices and Other Exogenous Variables	Product Shares				Factor Shares			Profit Function
	Roundfish	Yellowtail Flounder	Other Flounders	All Others	Capital	Labor	Fuel[a]	
Intercept	15.267 (2.793)	−.706 (1.058)	16.818 (2.014)	7.449 (1.792)	−9.317 (.739)	−9.763 (1.195)	−18.747 (2.608)	130.965 (10.370)
1981 Dummy	−.525 (.159)	.010 (.044)	−.384 (.145)	.205 (.107)	.248 (.067)	.233 (.118)	.212 (.075)	−5.666 (1.893)
New Bedford Dummy	.090 (.266)	.271 (.083)	.264 (.223)	−.318 (.186)	−.078 (.122)	−.182 (.207)	−.048 (.128)	2.518 (3.509)
Rhode Island Dummy	−.927 (.236)	.358 (.090)	−.351 (.237)	.030 (.146)	.052 (.110)	.501 (.181)	.337 (.039)	−6.498 (2.905)
Maine Dummy	−.948 (.297)	.089 (.074)	−.353 (.249)	.359 (.223)	.262 (.123)	.300 (.227)	.291 (.142)	−6.261 (3.614)
Roundfish	−.027 (.173)	.069 (.089)	1.347 (.269)	.036 (.138)	−.463 (.098)	−.782 (.201)	−.181 (.221)	
Yellowtail Flounders		.043 (.017)	−.124 (.086)	−.026 (.041)	.018 (.035)	.059 (.069)	−.039 (.054)	
Other Flounders			.474 (.160)	.596 (.140)	−.519 (.069)	−.841 (.150)	−.934 (.158)	
All Others				.163 (.040)	−.195 (.064)	−.441 (.101)	−.133 (.114)	
Capital					.105 (.009)	.682 (.064)	.372 (.057)	
Labor						−.032 (.063)	1.356 (.233)	
Fuel							−.442 (.879)	

* Standard errors in parentheses. Symmetry and linear homogeneity in prices directly imposed.

[a] Parameter estimates derived from symmetry and linear homogeneity constraints. Linearized standard errors in parentheses.

[8] Marshallian cross price product supply elasticities (V_{ij}) include both expansion and pure substitution effects since factor levels are allowed to change with changes in product prices (Sakai, 1974). A decrease in a product price

TABLE 3 Marshallian Product Supply and Factor Demand Elasticities*

Price	Roundfish	Yellowtail Flounder	Other Flounder	All Others	Capital	Labor	Fuel
Roundfish	.31ᵃ	2.03ᵃ	3.44ᵃ	1.45ᵃ	2.28ᵃ	3.13ᵃ	1.74ᵃ
	(.13)	(.90)	(.42)	(.47)	(.21)	(.46)	(.51)
Yellowtail Flounder	.15ᵃ	−.47ᵃ	−.10	.01	.06	−.04	(.19)
	(.07)	(.17)	(.13)	(.14)	(.07)	(.16)	(.12)
Other Flounder	1.66ᵃ	−.62	.38	2.68ᵃ	1.71ᵃ	2.58ᵃ	2.78ᵃ
	(.20)	(.87)	(.26)	(.48)	(.14)	(.34)	(.36)
All Others	.32ᵃ	.03	1.23ᵃ	−.15	.69ᵃ	1.31ᵃ	.60ᵃ
	(.10)	(.42)	(.22)	(.14)	(.13)	(.23)	(.26)
Capital	−.84ᵃ	−.30	−1.30ᵃ	−1.15ᵃ	−1.70ᵃ	−2.06ᵃ	−1.34ᵃ
	(.08)	(.36)	(.11)	(.22)	(.02)	(.15)	(.13)
Labor	−1.02ᵃ	.16	−1.75ᵃ	−1.94ᵃ	−1.84ᵃ	−1.36ᵃ	−3.55ᵃ
	(.15)	(.70)	(.24)	(.35)	(.13)	(.15)	(.54)
Fuel	−.587ᵃ	−.83	−1.90ᵃ	−.89ᵃ	−1.20ᵃ	−3.57ᵃ	−.42
	(.17)	(.54)	(.25)	(.39)	(.01)	(.13)	(2.01)

* Elasticities evaluated at 1980 mean levels for Gloucester, Boston, and other Massachusetts ports except New Bedford. Linearized standard errors in parentheses.

ᵃ Elasticities significant at 1%.

The mixed pattern of complementarity and substitutability one sees in Table 4 indicates that unanticipated catches of both regulated and unregulated species are possible in this joint-harvesting fishery. Catches exceeding the quota are discarded (or illegally landed). Individual species regulation thus does not necessarily reduce catches to the quota levels, and such regulation can be a counterproductive means to rebuild multispecies resource stocks. In fact, the otter trawl industry experienced just such effects when the Fishery Council attempted to regulate cod, haddock, and yellowtail as individual, nonjoint production processes.

TABLE 4 Allen Elasticities of Product Transformation*

	Yellowtail Flounder	Other Flounder	All Others
Roundfish	1.15	1.14	−0.09
Yellowtail Flounders		−1.42	−0.71
Other Flounders			1.41

* Elasticities evaluated at 1980 mean levels for all Massachusetts ports except New Bedford.

might induce movement along a given product transformation frontier (pure substitution effect) and changes in all the inputs along the new expansion path (expansion effect). Marshallian cross price factor demand elasticities similarly include expansion and substitution effects, and all inputs can be Marshallian complements (Sakai, 1974). Hicksian or compensated product supply elasticities (R_{ij}) hold input levels constant and provide pure substitution effects among product pairs along a transformation frontier. They are calculated from Marshallian elasticities by $[R_{ij}] = [V_{ij}] - [V_{ik}][V_{kl}]^{-1}[V_{ki}]$, where i, j are products and k, l are inputs (Lopez, 1984). Similarly, Hicksian or compensated factor demand elasticities hold output levels constant and measure pure substitution effects among input pairs along an isoquant. They are calculated by $[R_{kl}] = [V_{kl}] - [V_{ki}][V_{ij}]^{-1}[V_{ik}]$. Allen elasticities of product transformation and factor substitution are calculated from the Hicksian elasticities by $AET_{ij} = R_{ij}/U_j$ and $AES_{kl} = R_{kl}/U_l$.

Individual species regulation can generate economic inefficiency not only by the catch discards it causes but also by inducing nonoptimal input and output mixes. Economic inefficiency can also occur if trip limits are imposed and fishermen make more frequent trips, thereby increasing running time and fuel consumption. Pressures on the more accessible resource stocks also increase, which reduces catch productivity and increases costs. Landings taxes may also induce inefficient output proportions as the relative exvessel species prices are altered. Inefficient production can also be generated if fishermen increase input usage to maintain some overall minimum level of total revenue (perhaps to make vessel payments) when higher-valued species are regulated.

The alternative of regulating individual inputs is more effective and consistent with the structure of production. Because of the extensive Marshallian complementarity among inputs reported in Table 3, the levels of all inputs will decline with the restriction of any single input. The most readily monitored and managed input can be targeted for regulation. In turn, catch levels and pressures upon the resource stock will decline as indicated by the significant production elasticities between inputs and outputs of Table 3. Yet, even though the absolute level of each input declines, fishermen may still substitute unregulated for regulated inputs. Allen elasticities of substitution measuring the pure substitution possibilities are reported in Table 5. Both substitutability and complementarity among factor pairs are identified. Since unanticipated factor substitution is likely, more than one input can be regulated, thereby precluding inefficient factor and product proportions and keeping pressure on catches and resource stocks closer to targeted levels. Economic inefficiency from catch discards is eliminated. Input regulation is also easier to enforce and less costly than catch management since inputs can be monitored dockside rather than on the open sea. The composition of catch can even be controlled by regulatory agencies through minimum mesh sizes and other controls on gear selectivity.

A program regulating inputs might restrict entry to the industry by limiting the number of vessels. Unexpected expansions in productive capacity may then occur as fishermen attempt to appropriate any increases in economic rents by expanding harvesting capacity through larger vessels, engines, gear, and nets and by installing additional electronic equipment. Declines in economic rents and socially inefficient resource depletion are then likely. The elasticity of capital demand with respect to its own price, identified in Table 3, indicates that changes in capitalization are not difficult to make.[9] Crew sizes may also increase because labor is a complement to capital. Provisions against capacity expansion are therefore important to any limited-entry program.

Achieving targeted goals does not require particularly strong constraints because of the generally elastic substitution possibilities. In this sense direct quantity controls are as likely

TABLE 5 **Allen Elasticities of Factor Substitution***

	Labor	Fuel
Capital	−.45	.47
Labor		2.69

* Elasticities evaluated at 1980 mean levels for all Massachusetts ports except New Bedford.

[9] This result is also consistent with the finding of full static equilibrium reported earlier. In addition, the elastic own-price factor demands indicate that should output restrictions be tied to some measure of productive capacity, such as crew or vessel size, sizeable expansions of this input are likely. This happened in New England when individual species quotas were directly tied to crew sizes and crew sizes subsequently expanded.

to realize management goals as are indirect controls through taxes or fees. They also directly address the problems, are usually more amenable to change, and are under the control of a single Fishery Council rather than different state legislatures.

□ **Multiproduct cost structure.** The estimated structure of multiproduct costs is reported in Table 6. Economies of scope exist only between yellowtail flounder and each of the other sets of species. Yellowtail flounder is a pivotal species in the industry because cost savings accrue to vessels harvesting yellowtail with any of the other species. The estimated incremental marginal costs imply decreasing product-specific returns to scale for roundfish, other flounders, and all others. Declining product-specific marginal and average cost curves and increasing product-specific returns to scale are indicated for yellowtail flounder. The implied declining product-specific yellowtail supply curve may explain the significant negative own-price supply elasticity in Table 3 and some of the apparent difficulties in attaining convexity. Declining yellowtail stocks that are placed under excessive harvesting pressure can cause excess yellowtail harvesting capacity, and therefore the declining product-specific cost and supply curves.

The strong cost incentives to harvesting yellowtail because of economies of scope and the increasing product-specific returns to scale make the yellowtail resource stock vulnerable to intensive harvesting. Nonetheless, specialized yellowtail firms are unlikely because of the economies of scope realized by jointly harvesting yellowtail with other species.

The estimates of multiproduct returns to scale are .58 for 1980 and .62 for 1981. Multiproduct returns to scale are decreasing, and neither cost nor profit advantages accrue from harvesting more fish in fixed proportions while holding prices and resource abundance constant. As the scale of production expands for a given level of resource abundance, vessels fish in more marginal grounds and in more inclement weather, increase search time, and so forth. Firms should realize cost savings as the resource stocks recover under regulation.[10]

The multiproduct cost structure provides additional impetus to individual input regulation. Most output regulations affect yellowtail flounder because of the technological and cost interdependencies of joint harvesting. Firms then cannot fully enjoy economies of scope and product-specific returns to scale for yellowtail. Harvesting costs, economic efficiency, and possibly even the degree of firm diversification are affected throughout the industry. In contrast, input regulation does not affect económies of scope, although some firms' costs may increase if they cannot realize increasing product-specific returns to scale for yellowtail. Public regulation, even limiting the number of vessels, should also have minimal concern for a noncompetitive industry structure, since few cost incentives are present for firm amalgamation or a larger scale of production realized by fewer vessels.

TABLE 6 **Multiproduct Cost Structure***

	Measure of Weak Cost Complementarity			
	Roundfish	Yellowtail Flounder	Other Flounders	Incremental Marginal Costs
Roundfish				.004
Yellowtail Flounder	−.093			−2.183
Other Flounders	.004	−.083		.004
All Others	.009	−.189	.008	.018

* Evaluated at 1980 mean levels for all Massachusetts ports except New Bedford.

[10] As stocks recover, the transformation frontier should shift out, away from the origin, and increasing overall returns to scale are possible. Kirkley (1986) finds increasing overall returns to scale when estimating a multiproduct revenue function with resource abundance assessment levels specified as a technological constraint.

The actual choice of policy and instruments depends upon considerations beyond the scope of this study. To the extent possible, however, the regulatory program should be consistent with the structures of production and costs, and equally important, it should be readily accommodating to change.

6. Concluding remarks

■ This study finds that public regulation of multispecies fishing industries may previously have been inappropriately designed. Traditionally, the regulatory task has been conceived as one of either managing total industry catch and aggregate industry input, fishing effort, or *ad hoc* regulation of individual species as nonjoint production processes. The traditional bioeconomic model has formed the conceptual basis of this approach. Multispecies fisheries management can instead be approached as a process of regulating the production of individual multiproduct firms. In New England regulation consistent with this approach would directly regulate more than one input. Inefficient product and factor proportions, catch discards, and an inefficient cost structure would be prevented while reducing productive capacity and catch levels. In turn, resource stocks should recover and economic rents increase. Finally, only limited support is provided for the traditional bioeconomic model in the New England fishery studied.

Appendix

■ The hypothesis that production is nonjoint in inputs is rejected, since the likelihood ratio test statistic is 52.9 and the 1% critical value is 23.2. This implies that separate harvesting processes do not exist for the five species. (An anonymous reviewer suggests that trip limits, if effective, would make nonjoint production virtually impossible.) Input-output separability is rejected, since the test statistic is 116.6 and the 1% critical value is 30.6. Rejection of input-output separability with the translog form also implies rejection of a Cobb-Douglas form (Denny and Fuss, 1977). Weak separability of all outputs and inputs are each individually rejected because the chi-square statistics are 30.9 and 28.2, while the 1% critical values are 18.5 and 15.1 with 7 and 5 independent restrictions for outputs and inputs, respectively. These separability tests imply that consistent aggregates for total output (catch) and all inputs (fishing effort) and the traditional Cobb-Douglas fishery production function of bioeconomic models do not exist.

Weak separability is not rejected for either roundfish or flatfish, while weak homothetic separability is not rejected only for roundfish. The test statistics for weak separability of the two aggregates are 14.9 and 12.3, while the 1% critical value is 15.1. The test statistics for homotheticity are 4.5 and 21.5, while the 1% critical value is 9.2. A consistent aggregate can be formed only for roundfish.

The null hypothesis that the area dummy variables are unimportant is rejected since the test statistic is 158.7, while the 1% critical value is 38.9 for 21 independent restrictions.

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