Individual Transferable Quotes in a Multiproduct Common Property Industry
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Individual transferable quotes in a multiproduct common property industry

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Abstract. This paper extends the method of virtual prices for quantity constraints to provide inverse derived demand functions for quotas and quota market equilibrium and pricing. The approach is applied to evaluate the anticipated effects of a potential program of individual transferable quotas addressing the ill-structured property rights and market failure of a multi-product common property fishery. The results indicate that individual transferable quotas on multiple products may not generate the desired rents or achieve biological objectives, owing to limitations when joint products are regulated. However, an individual transferable quota on a single joint product may induce industry disinvestment and reduce overcapitalization.

Quotas individuels transférables dans une industrie où il y a propriété commune et plusieurs produits. Ce mémoire développe la méthode des prix virtuels pour des contraintes sur les quantités pour produire des fonctions de demande dérivées pour les quotas et les conditions d'équilibre sur le marché des quotas. Cette approche est utilisée pour évaluer les effets anticipés d'un programme potentiel de quotas individuels transférables pour corriger la mauvaise structure des droits de propriété et les faillites du marché dans des pêcheries en propriété commune à plusieurs produits. Les résultats montrent que cet instrument peut ne pas générer les rentes désirées ou ne pas atteindre les objectifs biologiques désirés à cause des difficultés engendrées par la réglementation de produits conjoints. Cependant, un quota individuel transférable sur un seul produit peut entraîner un désinvestissemnent dans l'industrie et réduire la surcapitalisation.

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I. INTRODUCTION

Individual transferable quotas (ITQs) increasingly are applied to control overcapitalization or excess production and internalize external costs in industries exploiting resources held in common (fishing, grazing, timber harvesting on public lands). ITQs can also help to control excess production and economic inefficiency associated with unstable market conditions, such as agriculture in the United States, the European Community, and Japan, or private production involving a quasi-public input (taxis or trucks using a public highway). ITQs also regulate air pollution (marketable emission permits), water resources, wastes, and international trade.

With ITQs, firms own transferable quantities of an overall production quota. Firms trade these ITQs; rents and market prices for the ITQs develop; and gains from trade are enjoyed, as firms with advantages in costs or capacity bid quota away from other firms. Production and investment decisions are made considering all costs, including formerly unpriced common property resources. Industries reorganize on efficiency grounds given overall quota.

Several fundamental issues concern regulators and industry when they plan an ITQ program: expected market price and economic rents; gains in efficiency from quota trade; and potential effects on firm investment incentives. Resolution of these issues would enable better evaluation and planning of prospective ITQ programs.

This paper addresses these issues by finding an expected equilibrium market price for ITQs, economic rents, and gains from trade in a multiproduct open-access fishery that is currently unregulated by ITQs. The paper also examines problems particular to ITQs on multiple products. The paper builds upon recent advances in multiproduct capacity utilization (Segerson and Squires 1993) to assess the potential effects of quota trade upon the firm's investment incentives and implications for policy. The approach can evaluate the anticipated effects of potential programs of tradable input or output quantity controls in other industries.

The paper extends the virtual price framework of Rothbarth (1941) and Neary and Roberts (1980) for consumer quantity constraints – extended to the theory of the firm by Neary (1985), Fulginiti and Perrin (1993), and Squires (1994) – to allow for inverse derived demand functions for quotas, quota exchange among firms, and equilibrium market prices for the transferable quotas. The paper also develops the marginal rate of transformation and the direct elasticity of transformation for ITQs. In addition, the paper follows Lau (1976), where the firm's production decisions are made in two steps. In the first step, the vessel maximizes variable profits or revenues conditional upon the existing fixed factors. In the second step, over a longer time period, the firm adjusts its fixed factors to the appropriate size to maximize long-run profits.

In section II the industry and empirical model are described. In section III the data are described and the empirical results and implications for an ITQ program are evaluated. In section IV concluding remarks are given.

II. EMPIRICAL ANALYSIS

The potential effects of ITQs were studied for an open-access, multiproduct trawl fishery off northern California and southern Oregon. This region is the center of the thornyhead and sablefish fishery on the Pacific coast, which is conducted in the deep waters of the continental slope. Fleet overcapitalization and growing export demand from Japan, coupled with the absence of property rights, created harvests sufficient to threaten resource stocks, requiring command-and-control quotas on thornyheads in 1991 and on sablefish in 1985. These quotas, unlike ITQs, offer neither harvest rights nor transferability and thereby do not address the absence of property rights in an open-access fishery.

The industry is composed of many multiproduct firms. During each fishing trip, vessel operators directly plan production based on current market conditions, including competitive prices, given vessel, weather, and resource abundance constraints. Vessels apply inputs to the resource stock for a product flow in a stock-flow technology. A special case of profit maximization, revenue maximization, is the objective for the short production period of a fishing trip once a resource area has been selected (Kirkley and Strand 1988; Segerson and Squires 1993). Inputs are largely fixed, because boats cannot readily alter inputs at sea. Since vessel size or capital stock is fixed at the trip level and largely determines the level of other inputs over this short period of one to five days, the input bundle can be specified as a single, composite input, called fishing effort.[1]

1. Revenue function

The technology can be derived from a dual revenue (GNP) function for firms that maximize revenue subject to fixed inputs (McFadden 1978), including a single composite input (Diewert 1974). The revenue-maximizing production process for each vessel's fishing trip modelled by a non-homothetic generalized Leontief revenue function is (Kirkley and Strand 1988):[2]

$$R[P; Z] = \sum_i \sum_j \alpha_{ij}[P_i P_j]^{1/2} Z + \sum_i \alpha_i P_i Z^2 + \sum_i \sum_r \alpha_{ir} D_r P_i Z + \sum_i \sum_s \alpha_{is} Q_s P_i Z, \qquad (1)$$

where Z is the capital stock or fishing effort, measured by a vessel's gross registered tonnage (GRT). The competitive price of product Y_i is P_i, and $R[P;Z]$ represents maximum revenue given Z and the price vector P. D_r is the rth of two dummy variables for home ports in Brookings and Crescent City, and Q_s is the sth of three quarterly dummy variables for winter, spring, and fall. The port of Eureka in the

1 Formally, Leontief input separability is assumed.

2 Of the three most widely used flexible functional forms, the generalized Leontief and normalized quadratic allow analytical solutions of virtual prices and inverse demand functions, but the former gave better empirical results. The translog requires numerical solutions and numerical derivatives.

summer forms the base case. D_r account for spatial variations in access to resource stocks, species abundance, and port effects on prices. Q_s account for intertemporal variations in the technological constraints of weather and resource abundance.

Input-compensated supply equations $Y^*(P;Z)$, given by Hotelling's Lemma (McFadden 1978), are

$$\delta R[P;Z]/\delta P_i = Y_i^*(P;Z) = \sum_j \alpha_{ij}[P_j/P_i]^{1/2}Z + \alpha_i Z^2 + \sum_r \alpha_{ir} D_r Z + \sum_s \alpha_{is} Q_s Z, \tag{2}$$

where input compensation leaves the firm on the original transformation frontier corresponding to Z. Symmetry is imposed by the restriction: $\alpha_{ij} = \alpha_{ji}$, where $i \neq j$. The functional form automatically imposes linear homogeneity in prices.

2. *Individual transferable quotas*

The balance of this section discusses the unit quota rent, equilibrium ITQ market price, resource rents and gains from ITQ trade, stability of the ITQ market equilibrium, product transformation frontier, and effects of ITQs on firm asset values and investment incentives. Consideration is generally given first to imposition of a quota on either one of two species, thornyheads or sablefish, and then simultaneously on both of these species.

a. Unit quota rent

The input-compensated unit quota rent τ_1 of a quota on Y_1, in pounds per trip per vessel, is the difference between the output price and the virtual price:

$$\tau_1 = P_1 - \left\{ \frac{Z \sum_{j \neq 1} \alpha_{1j} P_j^{1/2}}{y_1 - \alpha_{11} Z - \alpha_1 Z^2 - \Omega_1 Z} \right\}^2, \tag{3}$$

where $\{\cdot\}^2$ is the virtual price ϕ_1 for the firm's quota y_1 and $\Omega_1 = \Sigma_r \alpha_{1r} D_r + \Sigma_s \alpha_{1s} Q_s$. Appendix A derives equation (3).

Equation (3) also forms the firm's inverse derived function for quota, $\tau_1[P;y,Z]$. This marginal valuation function derived from the technology indicates how much the firm's implicit marginal valuation of quota τ_1 must change to induce firms to hold one more unit of quota y_1. Because quota is exogenous, its value at the margin τ_1 adjusts, rather than quantity. Virtual prices and inverse derived demand functions for quotas are discussed in appendix B.

b. Market quota price

Horizontally summing the compensated inverse derived demand functions for each quota, equation (3), over all firms gives that quota's market inverse derived demand function. The exogenous overall quota forms the perfectly inelastic industry supply function. Equating the market demand to overall quota allows solution of the equilibrium ITQ market price. This price from a static model is equivalent to an auction market or optimal tax (Anderson 1988) or an annual lease or rental price when all quota units are exchanged. The aggregate quota is the same whether or not individual quotas are vested with transferable property rights.

Consider first an ITQ on a single product Y_1 with annual overall quota $\bar{Y}_1$. The equilibrium ITQ market price τ_1^* is numerically solved for each value of $\bar{Y}_1$ considered from

$$\bar{Y}_1 = \sum_k \left\{ \sum_{j \neq 1} \alpha_{1j} [P_j^k/(P_1^k - \tau_1^k)]^{1/2} Z^k + \alpha_{11} Z^k + \alpha_1 (Z^k)^2 + \sum_r \alpha_{ir} D_r Z^k + \sum_s \alpha_{is} Q_s Z^k \right\}, \tag{4}$$

where k indexes observations. Observations in this study are fishing trips of all vessels for which quota bound. The market ITQ price τ_1^* inserted into each firm's compensated inverse derived demand function gives the equilibrium allocation of ITQs by firm.

When ITQs are applied to multiple products, the solutions for the equilibrium ITQ prices are numerically solved from a system of simultaneous equations. These equations again match market-derived demand for each quota with its overall quota. Equilibrium ITQ prices τ_1^* and τ_2^* with overall quotas $\bar{Y}_1$ and $\bar{Y}_2$ are solved from

$$\bar{Y}_1 = \sum_k \left\{ \alpha_{12} [(P_2^k - \tau_2^k)/(P_1^k - \tau_1^k)]^{1/2} Z^k + \sum_{j=3} \alpha_{1j} [P_j^k/(P_1^k - \tau_1^k)]^{1/2} Z^k + \alpha_{11} Z^k + \alpha_1 (Z^k)^2 + \Omega_1 Z^k \right\} \tag{5}$$

$$\bar{Y}_2 = \sum_k \left\{ \alpha_{12} [(P_1^k - \tau_1^k)/(P_2^k - \tau_2^k)]^{1/2} Z^k + \sum_{j=3} \alpha_{2j} [P_j^k/(P_2^k - \tau_2^k)]^{1/2} Z^k + \alpha_{22} Z^k + \alpha_2 (Z^k)^2 + \Omega_2 Z^k \right\}. \tag{6}$$

c. Resource rents and gains from trade

Resource rent from ITQs come, in part, from cost savings as vessels adjust their scale of operation to the most efficient since they no longer face the open access pressures of the race to fish; they can allocate their fishing activity to the most favourable periods of the year. These rents also include cost savings from quota trade as more efficient firms purchase quota from less efficient firms. Finally, the ITQ rent for a single joint product is not strictly the rent solely from that output,

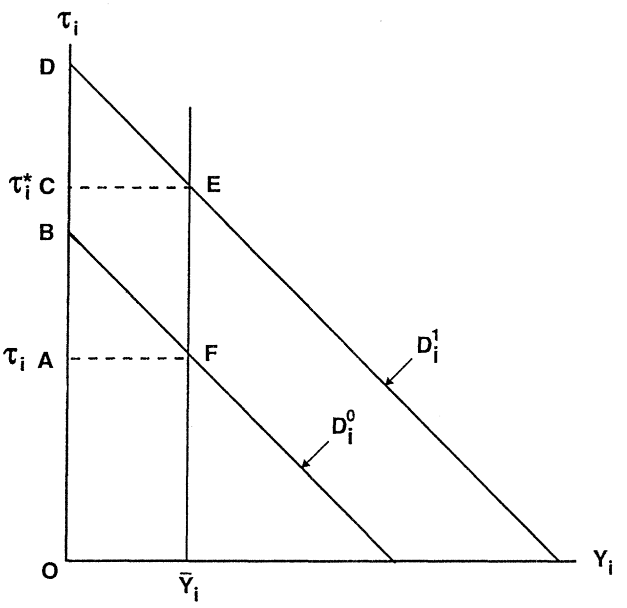

FIGURE 1 Inverse derived demand function and equilibrium market price for quota

but draws from the entire product line because of scope economies (showing up in equation (3) as terms involving P_j, $j \neq 1$).[3]

Figure 1 illustrates the increase in rent (producer surplus) from quota exchange as the reduced costs shift the market inverse derived demand curve for quota out from D_i^0 to D_i^1. Prior to quota trade, industry rent is the area under D_i^0 and above the unit rent (τ_i) line up to $\bar{Y}_i$, *ABF*. The gains from quota trade are the increase in industry rent by area *BDEF*. With ITQs on more than one output, the areas under each market inverse derived demand curve can simply be summed to give total rent for all quotas; simultaneous estimation of equilibrium ITQ prices from equations (5)–(6) assures path independency of rent.

Rents and gains from trade are calculated as follows using Mathematica. To obtain rent prior to trade but after quota allocation, the inverse derived demand function for each binding observation is integrated from 0 to the vessel's initial quota allocation y_i and then summed over all binding observations to give the total value. Rent (producer surplus) prior to trade is the difference between this area (implicit total willingness to pay) and the implicit total value (implicit unit rent times overall quota). We can evaluate rent after trade first by finding the quota holding for each observation corresponding to the ITQ price τ_i^*, second by integrating the inverse derived demand function for each observation from 0 to

3 An anonymous referee noted that a change in effort made to catch one species also affects the catch of other species and thereby the rent derived from them.

that post-trade quota holding, third by summing over all binding observations, and fourth by subtracting the value actually paid. Gains from trade is the difference in rent (producer surplus) after trade and before trade.

The short-run rent and producer welfare gains conditional on capital stock could closely match the long-term rent after vessels adjust their capital stock, and some vessels exit the industry if the existing overcapitalized capital stock largely represents sunk costs with minimal economic value.[4] If capital costs represent sunk costs, then the long-run efficiency gains largely come from reduced reinvestment, particularly from scrapped exiting vessels, as the race to fish halts.

d. ITQ market stability

Stability of the ITQ market and ITQ prices for changes in prices of unregulated outputs, quota holdings, or quasi-fixed factors can be evaluated by price flexibilities of the ITQ market price τ_i^* for y_i. These flexibilities indicate how much ITQ price must change to induce firms to adjust their quota holdings. Small flexibilities indicate stability in the sense that changes in exogenous variables result in small changes in endogenous variables. Price stability in the face of exogenous shocks provides a more favourable planning and production setting and reduces uncertainty.

Changes in exogenous variables shift the quota y_i's inverse derived demand function through ϕ_i^* and thus τ_i^*, which leads to a new equilibrium ITQ price τ_i^*. Thus, $\delta\tau_i^*/\delta y_j = -\delta\phi_i^*/\delta y_j > (<)\ 0,\ i \neq j$, for q-complements (substitutes). Moreover, $\delta\tau_i^*/\delta y_i = -\delta\phi_i^*/\delta y_i \leqq 0$. The matrix $[\delta\tau_i^*/\delta y_j]$ gives the production analogue to the Antonelli matrix of inverse consumer demand (cf. Anderson 1980; Antonelli 1886). When y_i and unregulated output Y_j are complements (substitutes), $\delta\tau_i^*/\delta P_j > (<)\ 0$. For example, when outputs Y_i and Y_j are complements, increases in P_j shift out the inverse derived function for quota y_i, thereby increasing τ_i^* and rent. For a normal technology (Sakai 1974), in which input-output relationships are not regressive, $\delta\tau_i^*/\delta Z \geqq 0$, also shifting out quota demand. Price flexibilities evaluated at τ_i or τ_i^* evaluate these effects.

The compensated price flexibility of τ_1 for P_j is

$$E_{\tau Pj} = \frac{\delta \ln \tau_1}{\delta \ln P_j} = \frac{-\alpha_{1j}P_j^{1/2}Z^2 \sum_{j\neq 1} \alpha_{1j}P_j^{1/2}}{(y_1 - \alpha_{11}Z - \alpha_1 Z^2 - Z\Omega_1)^2 \tau_1}. \tag{7}$$

By homogeneity of degree one in prices, $E_{\tau P1} = 1 - \Sigma_{j\neq 1} E_{\tau Pj}$.

The compensated quota flexibility of τ_1 for y_1 is

$$E_{\tau y1} = \frac{\delta \ln \tau_1}{\delta \ln y_1} = \frac{2y_1 Z^2 \left(\sum_{j\neq 1} \alpha_{1j}P_j^{1/2}\right)^2}{(y_1 - \alpha_{11}Z - \alpha_1 Z^2 - Z\Omega_1)^3 \tau_1}. \tag{8}$$

4 This follows because alternative productive opportunities could be few in other fisheries, which are frequently overcapitalized and overexploited, and vessel markets may be glutted (cf. Clark et al. 1979).

The compensated scale flexibility of τ_1 for Z is

$$E_{\tau Z} = \frac{\delta \ln \tau_1}{\delta \ln Z} = \frac{-2Z^2 \left(\sum_{j \neq 1} \alpha_{1j} P_j^{1/2} \right)^2 (y_1 + \alpha_1 Z^2)}{(y_1 - \alpha_{11} Z - \alpha_1 Z^2 - Z\Omega_1)\tau_1}. \tag{9}$$

e. Product transformation frontier

The industry product transformation frontier limits adjustments in quota portfolios with trade or exogenous changes in quotas and affects volatility of price formation of endogenous ITQ prices.[5] This frontier's slope and curvature with respect to Y_1 and Y_2 is described by the marginal rate of transformation for $\bar{Y}_1$ and $\bar{Y}_2$, MRT$_{12}$, and direct elasticity of transformation σ_{12} between $\bar{Y}_1$ and $\bar{Y}_2$. Once the exogenous overall quotas are set, endogenous MRT$_{12}$ at that point determines the market-clearing price ratio τ_1^*/τ_2^*. At the optimum, $\text{MRT}_{12} = -d\bar{Y}_2/d\bar{Y}_1 = \tau_1^*/\tau_2^*$.

The symmetric, two-price, two-quota σ_{12} measures the responsiveness of the quota mix ratio to changes in the MRT$_{12}$ at the optimum: $\sigma_{12} = [d(\bar{Y}_2/\bar{Y}_1)/d(\text{MRT}_{12})]$ $[\text{MRT}_{12}/(\bar{Y}_2/\bar{Y}_1)] = [d(\bar{Y}_2/\bar{Y}_1)/d(d\bar{Y}_2/d\bar{Y}_1)]$ $[(d\bar{Y}_2/d\bar{Y}_1)/(\bar{Y}_2/\bar{Y}_1)]$. Substituting the equilibrium condition $d\bar{Y}_2/d\bar{Y}_1 = -\tau_1^*/\tau_2^*$ and further derivation yields[6]

$$\sigma_{12} = \frac{\left[\dfrac{1}{\bar{Y}_1} - \dfrac{\tau_1^*}{\tau_2^* \bar{Y}_2}\right]}{\dfrac{1}{\tau_1^*}\left[\dfrac{\delta\tau_1^*}{\delta\bar{Y}_1} - \dfrac{\delta\tau_1^*}{\delta\bar{Y}_2}\dfrac{\tau_1^*}{\tau_2^*}\right] - \dfrac{1}{\tau_2^*}\left[\dfrac{\delta\tau_2^*}{\delta\bar{Y}_1} - \dfrac{\delta\tau_2^*}{\delta\bar{Y}_2}\dfrac{\tau_1^*}{\tau_2^*}\right]}. \tag{10}$$

The total rent share of $\bar{Y}_2$ increases (decreases) relative to $\bar{Y}_1$ according as $\sigma_{12} <$ $(>)$ 1 (Sato and Koizumi 1973).

f. Shadow prices

The shadow price of the quasi-fixed factor Z, W^*, is

$$\delta R[P; Z]/\delta Z = W^* = \sum_i \sum_j \alpha_{ij}[P_i P_j]^{1/2} + 2\sum_i \alpha_i Z + \sum_i \Omega_i P_i, \tag{11}$$

where W^* denotes the firm's implicit marginal valuation of Z, and $\Omega_i = \Sigma_r \alpha_{ir} D_r + \Sigma_s \alpha_{is} Q_s$. W, used later in the paper, denotes the capital services price or market rental rate of Z.

The shadow price of Z under quota y_1, $\tilde{W}^*$, is the same as it is without quotas when evaluated at $P_1 = \phi_1$ (Fulginiti and Perrin 1993). Substituting ϕ_1 from (3) into (11) gives ($\sim$ denotes under quota)

5 The production possibilities frontier reflects output combinations, holding effort Z constant. It is described by the outer boundary of the producible output set.

6 The derivation follows equations (1)–(18) of Powell and Gruen (1968) and is available from the authors upon request.

$$\tilde{W}^* = \alpha_{11}\left[\frac{Z\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}}{y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z}\right]^2 + \sum_{j\neq 1}\alpha_{1j}\left[\frac{Z\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}}{y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z}\right]P_j^{1/2}$$

$$+\sum_{i\neq 1}\sum_{j\neq 1}\alpha_{1j}[P_iP_j]^{1/2} + 2\alpha_1\left[\frac{Z^{3/2}\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}}{y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z}\right]^2$$

$$+2\sum_{i\neq 1}\alpha_iP_iZ + \Omega_1\left[\frac{Z\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}}{y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z}\right]^2 + \sum_{i\neq 1}\Omega_iP_i. \tag{12}$$

g. Firm asset values and investment incentives under quotas

Much of the private (as opposed to social) burden of adjustments to changes in economic conditions, including changes in output prices and quotas, falls on W^*, the firm's implicit rental price for Z. Information on the impact of ITQs on W^* is valuable to firms making investment plans or selling their assets, allowing them to time market valuation, to gauge asset stability, and to arrange finances to dampen ups and downs or take advantage of liability value changes.

Over a longer time period, when a firm can adjust its quasi-fixed factors Z, quota trade may lower the firm's rate of capacity utilization (CU), creating disinvestment incentives and perhaps reduced industry capitalization. The cost-gap multiproduct CU measure for the revenue-maximizing firm with a single quasi-fixed factor prior to quotas is: $\mathrm{CU}_C = W^*/W$ (Segerson and Squires 1993). CU_C contains information on the implicit costs of divergence from long-run equilibrium. CU_C once under quota, denoted $\widetilde{\mathrm{CU}}_C$, is formed by substituting virtual prices ϕ_i for P_i for outputs under quota into $\mathrm{CU}_C = W^*/W$. Purchase (sale) of quota increases (decreases) W^* and CU_C and, for quota sellers, CU_C and W^* may decline enough to prompt industry exit. For a normal technology, $\delta\tilde{W}^*/\delta y_i$, $\delta\tilde{W}^*/\delta P_j$, $\delta\widetilde{\mathrm{CU}}_C/\delta y_i$, $\delta\widetilde{\mathrm{CU}}_C/\delta P_j \geqq 0$, $i \neq j$, where i indexes an output under quota and j indexes an output not under quota.

The elasticity of $\tilde{W}^*$ or $\widetilde{\mathrm{CU}}_C$ for changes in the quota y_1 is

$$\frac{\delta \ln \tilde{W}^*}{\delta \ln y_1} = \frac{-y_1\left[Z\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}\right]^2[y_1/Z+\alpha_{11}+3\alpha_1Z+\Omega_1]}{\tilde{W}^*(y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z)^3}. \tag{13}$$

The elasticity of $\tilde{W}^*$ or $\widetilde{\mathrm{CU}}_C$ for changes in P_j is

$$\frac{\delta \ln \tilde{W}^*}{\delta \ln P_j} = \frac{\alpha_{1j}\sum_{j\neq 1}\alpha_{1j}P_j^{1/2}Z^2(2\alpha_1Z^2+y_1)}{\tilde{W}^*(y_1-\alpha_{11}Z-\alpha_1Z^2-\Omega_1Z)^2} + \frac{\sum_{i\neq 1}\alpha_{ij}P_i^{1/2}}{\tilde{W}^*}. \tag{14}$$

By homogeneity of degree one in prices, $E_{\tilde{W}*1} = 1 - \Sigma_{j \neq 1} E_{\tilde{W}*j}$.

III. EMPIRICAL RESULTS

Vessel size affects trip length, hold capacity, weather capabilities, and area and depth fished. Thornyheads and sablefish are distributed with older and larger fish in deeper waters. Because these factors affect product mix and levels, the fleet was divided into vessels less than and greater than 75 GRT. There were 585 (444) observations or fishing trips on the sixteen smaller (fourteen larger) vessels. Six outputs were specified: Dover sole, thornyheads, sablefish, other flatfish, other rockfish, and a residual category for all other species.

a. Data and estimation

The output side data were from the PacFIN Research Data Base of the National Marine Fisheries Service (NMFS). Landings and revenues were recorded by species at the port of landing after fishing trips for each vessel. Output prices were implicitly formed and Divisia indices used for aggregated species groups with revenue shares as weights. The 1984 data are from the last year prior to trip quotas; so the data do not reflect behaviour induced by the trip quotas, and discards of unwanted fish should be inconsequential (discards are not reported). Vessel characteristics are provided by the U.S. Coast Guard. The Eureka Fishermen's Marketing Association identified vessels fitted with the high-speed winch required to fish in deep waters of the continental slope.

Costs were taken from confidential federal income tax returns. An unknown sample bias could develop, because most of the cost data concern vessels participating in NMFS loan guarantee or capital construction fund programs, and these vessels tend to be newer and more successful than most of the fleet. Data from income tax returns and PacFIN were matched for consistency by several methods but most importantly for deviation in revenue less than 15 per cent and for fuel consumption consistent with fishing time and vessel size. Data with extraordinarily large cost shares were closely scrutinized.

The system of input-compensated supply equations, equation (2), was initially estimated by ordinary least squares for the last unregulated year, 1984. Heteroscedasticity was found, with error variance proportional to Z^2 (Parks 1971). Each equation was subsequently divided by Z. Zellner's seemingly unrelated regression iterated to convergence gave maximum likelihood estimates.[7]

7 The functional form is assumed to be exact rather than an approximation, and the errors are from optimization rather than approximation and apply only to the input-compensated supply equations. The problem of zero outputs also arose in some instances, creating a limited-dependent variable problem, which may cause bias and non-normality of the residuals. The procedure of Lee and Pitt (1987) solves this problem using virtual prices, but it is not computationally feasible with the number of variables in this study. A Box-Cox transformation could be used, but it was rejected on the grounds that a particular form of non-normal disturbances is assumed prior to transformation. The small value of 0.01 was substituted for zero when necessary. A sensitivity analysis for the large-vessel group used values of 0.1 and 0.001; the log-likelihood function changed by 0.099 per cent and 0.246 per cent, respectively. A few parameter values (particularly those for effort) changed by as much as 5 per cent, but price elasticities appeared to be robust.

TABLE 1
Parameter estimates of compensated supply functions: vessels < 75 GRT

Prices and other exog. variables	Quantity supplied of Dover sole	Thornyheads	Sablefish	Other flatfish	Other rockfish	All others
Effort	196.802 (20.601)	6.629 (8.135)	74.667 (17.920)	14.023 (5.203)	24.997 (9.518)	17.153 (2.544)
Effort squared	−1.379 (0.325)	0.304 (0.136)	0.041 (0.137)	0.172 (0.090)	0.476 (0.161)	−0.101 (0.042)
Brookings dummy	−32.311 (12.376)	−1.664 (5.152)	−2.655 (5.232)	5.911 (3.391)	3.391 (6.120)	12.411 (1.594)
Crescent City dummy	7.862 (10.183)	34.030 (4.303)	9.056 (4.388)	−11.265 (2.857)	−23.971 (5.168)	−0.837 (1.365)
Winter dummy	−1.749 (11.168)	9.253 (4.711)	−0.324 (4.880)	11.265 (3.067)	−25.741 (5.536)	−6.412 (1.558)
Spring dummy	28.045 (10.117)	−0.459 (4.221)	15.972 (4.273)	1.566 (2.778)	−0.784 (4.981)	−4.330 (1.298)
Fall dummy	9.826 (11.644)	11.249 (4.882)	2.389 (4.932)	1.985 (3.190)	−21.707 (5.744)	−6.694 (1.518)
Dover sole		9.697 (3.811)	−25.964 (11.493)	5.634 (3.262)	15.402 (3.790)	0.326 (1.676)
Thornyheads			13.182 (3.544)	−4.646 (1.664)	−16.219 (2.478)	−1.316 (0.694)
Sablefish				−7.461 (3.317)	−7.520 (3.322)	−0.944 (2.023)
Other flatfish					2.361 (1.331)	0.109 (0.463)
Other rockfish						0.340 (0.449)

NOTES
Generalized Leontief functional form. Symmetry and linear homogeneity in prices imposed. Standard errors in parentheses. Apparent heteroscedasticity required estimation of supply per unit of effort.

The parameter estimates for the smaller (larger) vessels are reported in table 1 (Segerson and Squires 1993). The generalized R^2 for equation (2) prior to the heteroscedasticity correction was 0.97 (0.99) for smaller (larger) vessels. $R[P;Z]$ is increasing and concave in Z at the mean in both cases.

Kulatilaka's (1985) significance test at sample means for the null hypothesis $W^* = W$ gave t-ratios of 4.73 for small and 0.06 for large vessels. During recent years, vessels progressively migrated farther offshore to harvest unexploited resource stocks in ever-deeper waters of the continental slope. Before the introduction of ITQs, this high-volume, open-access strategy favoured larger-sized vessels. Thus, before ITQs, smaller group vessels had high rates of CU and economic incentives to expand fishing effort. In contrast, open-access fishing effort of larger group vessels was in full static equilibrium.

TABLE 2
Input-compensated supply elasticities: vessels < 75 GRT

Prices and effort	Quantity supplied of Dover sole	Thornyheads	Sablefish	Other flatfish	Other rockfish	All others
Dover sole	−0.027 (0.035)	0.237* (0.080)	−0.330 (0.146)	0.167 (0.097)	0.447* (0.110)	0.071 (0.363)
Thornyheads	0.032* (0.013)	0.019 (0.021)	0.150* (0.040)	−0.127* (0.045)	−0.456* (0.068)	−0.285 (0.141)
Sablefish	−0.081 (0.036)	0.268* (0.062)	0.383 (0.168)	−0.184 (0.082)	−0.182 (0.081)	−0.171 (0.366)
Other flatfish	0.025 (0.217)	−0.137* (0.042)	−0.113 (0.050)	0.096* (0.031)	0.068 (0.039)	0.026 (0.108)
Other rockfish	0.049 (0.214)	−0.363* (0.048)	−0.082 (0.036)	0.046 (0.026)	0.108* (0.037)	0.056 (0.075)
All others	0.001 (0.085)	−0.025 (0.012)	−0.008 (0.018)	0.002 (0.008)	0.005 (0.007)	0.303* (0.072)

NOTES
*Statistically significant at 1 per cent. Calculated at sample mean for Eureka in the summer. Linearized standard errors in parentheses calculated by the delta method. Computed following Kirkley and Strand. Supply elasticities for vessels ≧ 75 GRT reported in Segerson and Squires (1993).

b. Price elasticities

Table 2 (Segerson and Squires 1993) reports the own- and cross-price input-compensated supply elasticities evaluated at the sample mean for smaller (larger) vessels. Own-price elasticities are all non-negative except for Dover sole (sablefish) for smaller (larger) vessels, both of which are negative but statistically insignificant. The cross-price elasticities indicate both complementarity and substitutability among product pairs and all are highly inelastic. The pervasive inelasticity even prior to quota indicates little flexibility to alter species mix, which declines after quota, owing to Le Chatelier effects (Squires 1994).

c. ITQ allocation

In this study, overall quota was set on the basis of the year's actual catch. Specifically, to limit banking or retention of quota by firms producing less than quota, the quota level for trips, when binding, is summed over all binding trips to give the total overall quota. Some trips had catch levels too small to bind, and these were not counted in the overall quota.[8] ITQs were then initially allocated gratis to each vessel in one-pound units. Because the model uses trip-level data and supply curves (summed to an annual supply for each vessel), each vessel can allocate its annual

8 If quota was allocated to those vessels for which quota was not binding, this additional overall quota would simply increase $\bar{Y}_i$ and K, the total number of observations, in equations (4), (5), (6), and lower τ_i^*.

ITQ holdings across all its trips to obtain the optimum catch per trip and enjoy optimum short-run multiproduct economies of scale. Resource stocks were at or above the levels associated with maximum sustainable yield (MSY). Hence, because the production technology is conditional on the resource stock level, empirical results corresponded to MSY resource stock levels.

Two of the most contentious economic and social issues facing any ITQ program are concentration of wealth and disruption of existing industry and community structures. In addition, major biological concerns are to limit excessive depletion of local stocks and sexually mature females. Thornyheads are a very long-lived and slow-growing fish and sablefish are distributed with juveniles inshore and sexually mature females offshore. Larger, older fish of both species are located in deeper offshore waters. Hence, there is concern to disperse the catch more evenly over the geographic area and to prevent overexploitation of higher-yielding, relatively unexploited offshore stocks, which also contain a larger proportion of the spawning biomass. For these and other reasons (cf. Copes 1986), ITQs were separately allocated to the small and large vessel groups and ITQ trade between groups was prohibited. The restrictions spatially distribute effort by maintaining small vessels inshore and large ones offshore. The restrictions on trade and initial allocation may limit potential gains from ITQ trade and industry restructuring, but they do satisfy the social, political, and biological concerns of the Pacific Fishery Management Council.[9]

1. Market equilibrium quota price and resource rents

a. Individual outputs

Equilibrium ITQ market prices for thornyheads (T) and sablefish (S), τ_i^*, $i = T$, S, were solved from equation (4) for each vessel group for a wide range of quota allocations at (1) all binding observations; (2) mean prices and GRT for four GRT size classes; and (3) the overall sample mean. The revenue functions, output supply equations, and inverse derived demand functions satisfied necessary conditions for convexity at the sample mean, but at some observations these conditions failed.[10] These observations were excluded in the first approach to calculate τ_i^* (otherwise,

9 Prohibiting trade limits concentration of ITQ holdings and hence concentration of wealth.

10 Certain regularity conditions (particularly convexity) are often violated over large sample regions with a flexible functional form (FFF). These violations can be for reasons other than failure to satisfy the model's behavioural assumptions. Wales (1977) showed that estimates of an FFF may violate regularity conditions even if the data came from a well-behaved technology. Restrictive functional forms that a priori satisfy all regularity conditions sacrifice flexibility and impose restrictive assumptions (homogeneity and separability). Imposing convexity in an FFF, either globally or over a region, is convenient for simulation work and is consistent with economic theory, but it also obscures economic responses and can give biased estimates of elasticities (Pollock and Wales 1992). Eliminating troublesome parameters can also give convexity, but it imposes unknown structure and bias upon the model and reduces flexibility. Eliminating observations causing violations also biases results. Evaluating results at a point more likely to be well behaved, such as the sample mean or point of approximation, is useful, but it masks results for individual firms. In short, all methods obscure economic relations. This paper blends an analysis of the well-behaved

TABLE 3
Equilibrium quota market price, total rent, and gains from trade

Overall quota (lbs)	Market price ($/lb) (1)	(2)	(3)	Trade gains (%)	Total rent ($) (1)	(2)	(3)
Small vessels and thornyheads							
285,600	0.1839	–	0.1056	61.1	30,086	–	62,383
280,000	0.2088	–	0.1884	77.6	20,155	–	29,150
276,000	0.2176	0.0788	0.19526	89.1	16,544	77,972	26,751
270,200	0.2226	0.1857	0.19578	103.8	14,674	32,051	27,372
266,500	0.2276	0.2015	0.19588	119.9	12,691	25,712	28,460
253,200	0.2323	0.2066	0.19592	142.5	10,419	23,647	29,008
245,300	0.2352	0.2089	0.19593	167.4	9,255	23,440	30,231
230,000	0.2370	0.2101	0.19594	194.9	8,349	23,153	30,698
220,500	0.2371	0.2108	0.19595	214.7	8,491	23,056	31,663
Large vessels and thornyheads							
377,500	0.0730	0.2041	0.2071	35.0	90,045	121,482	96,383
369,600	0.1276	0.2171	0.2080	42.4	64,250	86,630	78,229
368,000	0.1674	0.2231	0.2086	51.6	45,908	83,378	74,483
360,800	0.1890	0.2264	0.20902	63.5	35,811	105,294	96,017
354,900	0.2024	0.2283	0.20933	69.5	28,461	93,924	84,328
348,000	0.2112	0.2296	0.20955	79.6	24,067	60,620	50,653
342,000	0.2174	0.2305	0.20973	88.4	20,813	71,097	60,846
340,000	0.2220	0.2311	0.20987	90.3	18,736	42,586	31,832
336,000	0.2253	0.2316	0.209981	107.9	17,081	33,965	22,863

NOTES
(1) τ calculated using all binding and well-behaved observations.
(2) τ calculated at overall sample mean.
(3) τ calculated at means of four vessel size classes.
Gains from trade calculated using all binding and well-behaved observations.

τ_i^* tended to be an increasing function of $\bar{Y}_i$).[11] Hence, each τ_i^* was assessed only for well-behaved binding observations in the first approach, and some bias was undoubtedly introduced.

b. Thornyheads

Fairly close values of τ_T^* were found by the three methods for both vessel groups except at highest quotas (table 3). Non-binding quotas precluded calculation of τ_T^* with means for large quotas with the small vessel group. Values of τ_T^* increased for both vessel groups as quota increasingly restricted production.

Proportional gains from trade were substantial for most of the initial quota allo-

individual observations and analyses at sample means with extensive knowledge of the industry and data to spark insights into the most probable economic relationships.

11 Quasi-concavity of quota for the quota-constrained revenue or profit function is equivalent to quasi-convexity of quotas for the same function when evaluated at virtual prices. For a general discussion of this type of relationship between the primal and dual representations of production technology, see Lau (1976).

TABLE 4
Equilibrium quota market price, total rent, and gains from trade for small vessels and sablefish

Overall quota (lbs)	Market price ($/lb) (1)	(2)	(3)	Trade gains (%)	Total optimum rent ($) (1)	(2)	(3)
510,300	0.0850	0.0355	0.0173	17.4	50,237	88,761	104,120
498,000	0.0899	0.0474	0.0321	18.4	46,487	79,460	92,360
494,000	0.0941	0.0578	0.0480	19.3	43,955	72,478	80,833
486,000	0.0986	0.0668	0.0559	20.5	40,946	66,146	75,570
477,700	0.1017	0.0748	0.0655	21.9	38,870	60,269	68,372
472,000	0.1057	0.0819	0.0738	23.3	36,556	55,834	63,077
459,000	0.1094	0.0882	0.0813	25.2	34,174	51,426	57,652
450,800	0.1117	0.0938	0.0879	27.5	32,753	47,487	52,836
430,300	0.1146	0.0989	0.0938	30.1	30,186	43,010	47,564
414,000	0.1170	0.1034	0.0990	32.9	28,416	39,553	43,477
396,000	0.1196	0.1075	0.1037	37.1	26,502	36,453	39,848

NOTES
(1) τ calculated using all binding and well-behaved observations.
(2) τ calculated at overall sample mean.
(3) τ calculated at means of four vessel size classes.
Gains from trade calculated using all binding and well-behaved observations.

cations for both small and large vessels (table 3), reflecting substantial intervessel efficiency differences.[12] Similar trade gains were found across methods for both vessel groups when the three evaluation methods were used, but the crucial property of a downward-sloping inverse derived demand function (which follows from convexity of the revenue function) deteriorated significantly using means for the four GRT classes of the small vessels.

c. Sablefish

The sablefish ITQ price τ_S^* was calculated for only the small vessel group, since the sablefish supply curve for large vessels, while statistically insignificant, was negatively sloped. This would otherwise give an upward-sloping inverse ITQ demand curve, for which it would not be possible to calculate an equilibrium ITQ price. Hence, τ_S^* for large vessels was assumed to follow τ_S^* for small vessels.[13] τ_S^* was about one-half sablefish's mean output price and smaller than thornyhead's ITQ price τ_T^* (table 4). The proportional trade gains were fairly large, reflecting sizable differences in intervessel efficiencies, although they were smaller than those for thornyheads.

Resource rents are relatively small for each vessel group, owing to regulation

12 Proportional gains were calculated as (rent after trade − rent before trade)/(rent before trade).
13 For large vessels, the sablefish quota establishes a perfectly inelastic supply curve to the left of the perfectly inelastic notional supply curve, with the difference equalling at-sea discards. Large vessels would demand full sablefish quota only to the extent they were induced to legally land this excess production.

of a single species in a small industry (tables 3–4). The rents are smaller than the regulatory costs of planning, implementing, and enforcing an ITQ program.

d. Multiple outputs

ITQs on multiple outputs (species) face the problem of individual regulation of joint products. Limited vessel product transformation possibilities hinder matching production and quota holdings. In addition, aggregate quotas are often set on a biologial basis under the implicit assumption of non-jointness, but implied production rates are incompatible with those of joint production (Kirkley and Strand 1985; Squires 1987).

Three basic possibilities are represented in figure 2 using the industry's input-compensated product transformation frontier for sablefish and thornyheads. First, at A, overall quotas for thornyheads and sablefish $\bar{Y}_T^0$ and $\bar{Y}_S^0$ exactly match joint production possibilities and $\mathrm{MRT}_{TS} = -d\bar{Y}_S/d\bar{Y}_T = \tau_T^*/\tau_S^*$ as endogenous ITQ prices adjust to clear the ITQ markets. None the less, joint production possibilities and $\bar{Y}_T^0$ and $\bar{Y}_S^0$ are not generally expected to match if quotas are biologically set. Second, species with binding quotas are fished at appropriate sustainable levels and the other regulated species are underfished. At B, exogenous $\bar{Y}_T^0$ matches thornyhead production possibilities at A, but $\bar{Y}_S^1$ is in excess supply at AB $(\bar{Y}_S^1 - \bar{Y}_S^0)$. A thornyhead ITQ price τ_T^* forms (since quota supply equals demand) but the sablefish ITQ price τ_S^* is zero and $\mathrm{MRT}_{TS} = \tau_T^*/\tau_S^* = \tau_T^*/0 =$ infinity.[14] At C, $\bar{Y}_S^0$ matches sablefish production possibilities at A, but $\bar{Y}_T^1$ is in excess supply AC $(\bar{Y}_T^1 - \bar{Y}_T^0)$. Positive τ_S^* forms, but $\tau_T^* = 0$ and $\mathrm{MRT}_{TS} = 0/\tau_S^* = 0$.

Third, some overall quotas may match industry production possibilities, but quotas of overharvested species are set below production possibilities, setting the stage for excess production beyond quota. When overall quotas are $\bar{Y}_T^0$ and $\bar{Y}_S^2$, as at D, and $\bar{Y}_T^0$ binds overall production first (as in a mathematical programming model), $\bar{Y}_T^0$ matches thornyhead production possibilities at A, but sablefish production possibilities exceed $\bar{Y}_S^2$ by AD $(\bar{Y}_S^0 - \bar{Y}_S^2)$. At F, $\bar{Y}_S^0$ matches sablefish production possibilities at A, but thornyhead production possibilities exceed $\bar{Y}_T^2$ by AF $(\bar{Y}_T^0 - \bar{Y}_T^2)$. At E, industry production possibilities of sablefish and thornyheads exceed $\bar{Y}_S^2$ and $\bar{Y}_T^2$ by EF and ED. Over the long run, at points D, E, or F, excess production potential persists until disinvestment lowers the transformation frontier. Finally, in a dynamic context, overage rents represent opportunity costs from forgone future earnings rather than current benefits.

As in Australia and New Zealand, a de facto expansion of the binding species quota could occur when production in excess of quota is disposed of at sea (with high fish mortality), heavily penalized, or public programs induce landings of these

14 Anderson (1989) first discussed non-zero ITQ price formation. A similar problem -- the complementarity problem – is encountered with computable general equilibrium models. In linear programming, it would correspond to zero-valued shadow prices for slack variables. In terms of figure 1, point B in figure 2 corresponds to $\bar{Y}_2$ placed to the right of the horizontal intercept of the market inverse derived demand for sablefish quota, so that the ITQ price is zero.

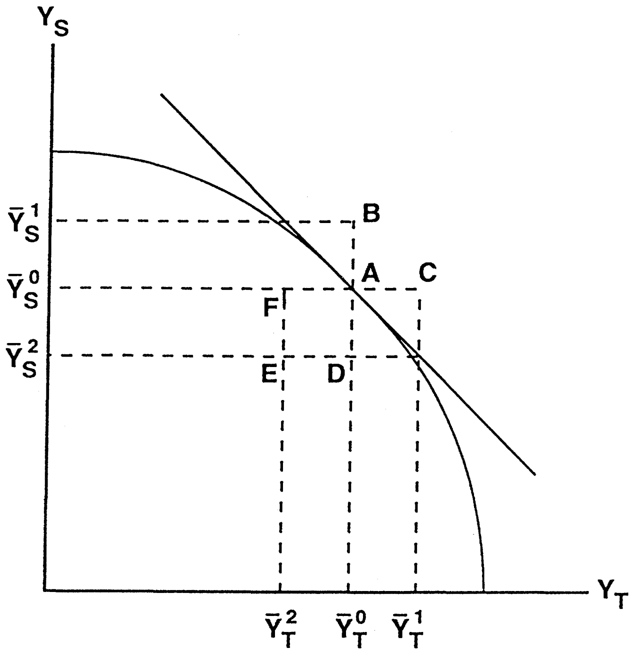

FIGURE 2 Industry product transformation frontier

quota overages.[15] But these programs are costly and cumbersome, participants may remain dissatisfied (New Zealand 1991), and harvests are unsustainable at appropriate rates for many species.

Excess production beyond quota may also persist at the firm level. A firm's limited ability to alter its product mix, heightened by Le Chatelier effects, and limited quota availability may preclude matching product mix with quota holdings.[16] Many of these joint products may be complements, requiring complementary trading patterns and quotas. In addition, a rising Dover sole price and falling prices of the other unregulated species will induce additional production along the notional

15 Allocations of quota in New Zealand were initially based upon erroneous stock assessments. The government subsequently eliminated, by fiat and without compensation, portions of each firm's portfolio of permanent property right for perpetual quota after initial allocations of quota were exchanged.

16 This problem is aggravated for species that are less uniformly distributed over the ocean bottom, since it is more difficult to gauge actual quantities caught with each tow of the net.

Consider two substitute outputs Y_i and Y_j under quotas y_i and y_j, where the firm's current catch exactly matches its quota holdings for y_j and additional y_j is unavailable on the market. The firm also has sufficient quota holdings to increase production of Y_i. As the firm harvests more Y_i, it moves out along its notional supply curve for Y_i and attempts to substitute away from Y_j. But because substitution possibilities between Y_i and Y_j are limited (further limited by Le Chatelier effects), the firm continues to produce Y_j along the notional supply curve for Y_j and must dispose of $Y_j - y_j$. This disposal can be either at sea or by onshore landings induced by public programs or strict at-sea enforcement. Output complementarity between Y_i and Y_j aggravates the problem.

TABLE 5
Equilibrium quota market price, total rent, and gains from trade for small vessels and both thornyheads and sablefish

Overall quota (lbs)		Market price ($/lb.)		Trade gains	Total optimum
Thornys	Sable	Thornys	Sable	(%)	rent ($)
161,500	107,638	0.0957	0.0808	75.9	67,116
161,600	97,931	0.1519	0.0800	100.3	53,136
162,000	92,443	0.1721	0.0807	128.1	50,918
156,800	102,182	0.1950	0.0703	137.3	47,388
157,300	78,619	0.1957	0.0840	169.3	44,333
152,654	100,676	0.2149	0.0702	179.0	45,012

NOTE
Sablefish quota lowered until binding.

TABLE 6
Compensated elasticities of thornyhead unit quota rent at τ^*

Prices, effort, and quota	Small vessels	Large vessels
Prices of		
Dover Sole	1.218	0.119
Thornyheads	1.134	0.656
Sablefish	1.387	0.608
Other Flatfish	−0.696	−0.017
Other Rockfish	−2.428	−0.832
All Others	−0.116	−0.034
Quantities of		
Effort	2.589	1.440
Thornyhead quota	−1.516	−1.253

NOTES
Evaluated at sample mean for Eureka in the summer at ITQ price τ^* with ITQ of 1,000 (2,100) pounds per trip for small (large) vessels. $E_{\tau Pj} > (<) \ 0$ for complements (substitutes). $E_{\tau Z} \geqq 0$ for normal technology.

supply curves of sablefish and thornyheads, raising the possibility of harvests in excess of quotas. This follows because Dover sole is a complement to sablefish and thornyheads, and all other unregulated joint outputs are substitutes (table 6).

Thornyheads and sablefish equilibrium ITQ prices τ_T^* and τ_S^* were simultaneously numerically solved using equations (5)–(6) for well-behaved observations (table 5). The thornyhead quota bound first (it had a higher ITQ price τ_T^*), and excess sablefish supply (*AB* in figure 2) gave a zero-valued ITQ price $\tau_S^* = 0$ until sablefish overall quota was lowered ($\bar{Y}_S^1$ to $\bar{Y}_S^0$ in figure 2).

Total multispecies rents (table 5) are smaller than the sum of the individual rents of single-species ITQs for comparable quotas (tables 3 and 4). This arose partly from a Le Chatelier effect, since the additional constraint hindered feasible regions and reorganizations in production and subsequent ITQ trade, and also because the lowered sablefish quota reduced the actual sablefish quantity valued by any ITQ price. The alternative to achieve a positive equilibrium ITQ price for sablefish was to raise thornyhead's quota beyond its biological optimum, expanding the feasible region, reducing the Le Chatelier effect, and raising total rent at the cost of overfishing thornyheads. Over time, this policy is biologically unsustainable and rents drop.

Whether ITQs are applied to single or multiple species, these are maximum possible rents, since in practice less trade may occur, owing to thin markets, sequential and bilateral trade, and transactions and information costs (Lindner et al. 1992). Large sunk costs could also retard trade (vessels may be reluctant to trade if they do not plan to exit). Reduced trading and possibly highly variable price signals can undermine efficient choices of production, investment, and quota exchange, and can reduce rent and gains from trade. This problem may be aggravated for ITQs on joint products, since additional constraints should increase Le Chatelier effects and perhaps help to foster thin ITQ markets. The empirical results should thus be viewed as benchmarks.

e. Stability of the ITQ market

The small-vessel ITQ market has the potential for instability. The price flexibilities from the inverse derived demand functions for single quotas (table 6) suggest that rent, inverse derived demand for quota, and the market ITQ price for thornyheads (τ_T^*) – the constraining species and the one with the higher ITQ price – are more sensitive to changes in prices of other outputs, ITQ quantities, or effort for small than large group vessels. $\delta \ln \tau_T^* / \delta \ln y_T \leqq 0$, as expected for inverse derived demand, and the elastic values indicate that the fleet bears an immediate opportunity cost of revenue forgone with a small tightening of quota. Rent recovery through a unit tax, which lowers τ_T^*, may generate considerable resistance, particularly for small group vessels, owing to τ_T^*'s sensitivity to exogenous changes in unregulated output prices and quota adjustments; a less disruptive lump sum tax or licence fee may be better accepted.

The industry product transformation frontier for small vessels and quotas on both species suggests ITQ price instability. $\text{MRT}_{TS} = -d\bar{Y}_S / d\bar{Y}_T = \tau_T^* / \tau_S^*$, conditional on capital and the quota market in equilibrium, ranges from 1.1844 for the least restrictive quotas to 3.0613 for the most restrictive. The output expansion path slopes towards sablefish as quotas tighten, providing a non-homothetic expansion path for production under quotas. σ_{TS} ranges from -0.003 to -0.117, indicating substantial curvature at the optimum and increasing total rent share for sablefish. In sum, ITQ price ratios τ_T^* / τ_S^* can substantially and non-linearly change if the quota authority alters $\bar{Y}_T$ and $\bar{Y}_S$ by the same proportion, contributing to volatility and uncertainty in the ITQ market. τ_T^* / τ_S^* also changes substantially around any given quota combination point given the small σ_{TS}. Finally, because of the non-homotheticity, optimal taxes, equivalent to τ_T^* and τ_S^*, would not be constant and would be difficult to calculate.

2. Quota and capacity utilization

ITQ programs force firms to confront explicitly the privatized value of the resource and re-evaluate private investment decisions through W^* and CU in the light of full social and private costs. Changes in CUs were evaluated for both unit quota rents prior to quota exchange (τ_T) and ITQ prices formed from exchange (τ_T^*) for each vessel's trips using all binding (and well-behaved) observations for the more valuable and binding species, thornyheads. Quota prior to exchange sizably reduced CUs in all cases. After τ_T^* was formed through exchange, CUs climbed for firms buying quota and further dropped for firms selling quota.

Most values of W^* and CU for the small vessel group became negative with quotas pre-exchange but positive after trade. Owing to high initial CUs pre-quota, CUs after exchange declined for a few vessels by such a visible amount to suggest disinvestment and industry exit; these declines were for a few small group vessels, which were generally the larger ones of this group.

In contrast, CU markedly declined for most larger group vessels after exchange. W^*, and hence CU, often became negative, strongly signalling disinvestment or fleet exit, each vessel receiving a lump sum payment $\tau_T^* y_T$. These vessels tended to be the smaller of the larger group vessels. Several had cost incentives (lower ϕ_T) to purchase quota, but had low CU even prior to quota. Quota purchase lifted ϕ_T and W^*, but it was insufficient to give positive values of W^* and CU_C because the quota seriously lowered CU. The concentration of exit among the larger vessels in the small-vessel class and the smaller vessels in the large-vessel class suggests that medium-size vessels are relatively inefficient when the full social costs of production are explicitly considered.

Industry restructuring could be hampered by limited alternatives for exiting vessels. Private investment decisions, and CU in particular, would be evaluated in the light of small opportunity costs of capital (often sunk costs). Current overcapitalization and likely expansion of ITQ programs along the Pacific coast of Canada and the United States would depress vessel resale markets and further dampen the opportunity costs of capital. The consequent decline in W would raise $\text{CU}_C = W^*/W$. The expected cost savings from reduced reinvestment rates and disinvestment from overcapitalized open-access levels may not emerge, except over a protracted period as vessels reach the end of economic lives. The pace of industry restructuring may fall below that hoped.

Vessels most likely exiting would be those with negative post-trade W^*, giving a negative CU measure. Under this criterion, none of the small vessels exits, but nine of the fourteen larger ones still depart.

Also owing to irreversible investment and sunk costs, production in excess of quota (corresponding to points D, E, or F in figure 2) may persist. Slow disinvestment retards the industry product transformation frontier lowering to match overall quotas.

The firm's investment planning environment should stabilize following initial ITQ responses, even for large group vessels. After the ITQ's initial effects upon W^*, changes in most output prices and unit taxes generally have a minimal impact

TABLE 7
Elasticities of price and quota for shadow price of fishing effort

Prices and quota	Small vessels	Large vessels
Price of:		
Dover Sole	0.345	0.798
Thornyheads	0.281	0.702
Sablefish	0.400	2.736
Other Flatfish	−0.289	−0.110
Other Rockfish	−0.639	−3.902
All Others	−0.097	−0.223
Quantity of:		
Thornyhead Quota	1.759	1.521

NOTE
Evaluated at sample mean for Eureka in the summer for quotas of 1,000 (2,100) pounds per trip for small (large) vessels.

on implicit asset values ($\tilde{W}^*$) and thus $\widetilde{cu}_C$ (table 7). In contrast, marginal quota adjustments substantially affect $\tilde{W}^*$ and $\widetilde{cu}_C$, the elastic values arising through relaxation of Le Chatelier effects. The quota authority perhaps should resist tinkering and fine-tuning overall quotas and allocations.

IV. CONCLUDING REMARKS

The gains in economic efficiency under an ITQ program, given sunk costs in the vessel and limited alternatives for exiting vessels and labour, may be largely short run in nature. The long-term economic gains from reduced overcapitalization may come primarily from reduced reinvestment, may be smaller than hoped, and perhaps should be seen as a by-product of an ITQ program rather than as the direct goal. Even with ITQs, overcapitalization can remain the sword of Damocles for fisheries management.

The short-run gains in rents and efficiency from an ITQ on a single joint product in the fishery were limited. Potential benefits would be less than the regulatory costs of an ITQ program, calling into question the efficiency of an ITQ program as a generator of resource rents for a single joint product. Extending ITQ coverage to additional joint outputs may not improve the benefit-cost ratio as much as hoped, since total net benefits are limited by imbalances in aggregate quotas, by production in excess of quotas (social costs), and by Le Chatelier effects as additional constraints progressively bind firms' production and lower rents.

ITQ programs with joint products might regulate only the most important or biologically vulnerable outputs. ITQ prices still capture rents from unregulated joint products (through scope economies), and the process of matching aggregate quotas to industry production possibilities and ensuring non-zero equilibrium ITQ prices is simplified. In addition, problems of quota overages, Le Chatelier effects, and regulatory costs and complexity are lessened. To the extent that reducing overcapitalization and creating disinvestment incentives are deemed socially desirable, even an ITQ on a single joint product may offer a powerful stimulus. When investments in capital and labour are largely irreversible and sunk, programs to purchase vessels, retrain labour, or encourage early retirement may be appropriate.

Other issues remain for ITQs on joint products. Regulating additional outputs can escalate program costs, especially for enforcement and monitoring. Limited firm product transformation possibilities and imbalances between overall quotas and industry production possibilities may require costly public programs to induce fish landings otherwise discarded when insufficient quota is held and cannot be procured on the market.

Escalating program costs might be countered if fisher-pay regimes for enforcement and stock assessment, coupled with greater self-enforcement from resource stewardship, lower these costs and discards (Arnason 1990; Scott 1989). None the less, the ITQ property right remains incomplete, since it is for the resource flow (harvest), not the stock, leaving elements of open access and market failure (Scott 1989). The remaining incentives for firms to exceed quota contribute to higher program costs and discards. ITQs are *private* property rights for the resource *flow* but the resource *stock* remains under *public* ownership, and hence remains a public good. Also, resource assessments form a public good, since these assessments form the basis of overall and individual quotas benefiting all industry members. Hence, when assessments are organized, the problems of revealing preferences, pricing, and free ridership must be dealt with.

ITQs on joint products harvested by bottom trawling versus selective, directed fishing also require consideration. Some fishery managers think that bottom trawling should be proscribed because of indiscriminate joint production, environmental destruction of the bottom habitat, imbalances created in the ecosystem, and the failure of ITQs to value ecological damage. In addition, ITQs may create incentives for selective fishing that might otherwise be absent. Enhanced gear selectivity comes from gear innovation and by seasonal selection of geographic areas to fish. Directed fishing with ITQs can also motivate product and market development, such as shifting product form from frozen to fresh (Wilen and Homans 1992). Ex-vessel price increases can form a source of increased resource rents other than by cost reductions, although care must be given not to double count harvest sector gains, which are simply benefit transfers from onshore processors (e.g., on-board processing) or consumers. In some circumstances, joint-product trawling may remain when sunk costs are sizable; when scope economies from trawling outweigh revenue gains from fishing with selective gear; when market opportunities are limited for fish differentiated by quality or price; when there are important economies of size for large volumes of lifted biomass; for shrimp harvesting; or when species are highly migratory or schooling.

APPENDIX A: UNIT RENT FOR GENERALIZED LEONTIEF REVENUE FUNCTION

The unit rent τ_1 for the quota y_1 is derived from the unregulated supply curve for output Y_1. The input-compensated supply curve for the generalized Leontief functional form is

$$Y_1 = \sum_{j \neq 1} \alpha_{1j} \left[\frac{P_j}{P_1}\right]^{1/2} Z + \alpha_{11}Z + \alpha_1 Z^2 + \Omega_1 Z. \tag{A1}$$

Under the quota y_1, with corresponding virtual price ϕ_1, equation (A1) becomes

$$y_1 = \sum_{j \neq 1} \alpha_{1j} \left[\frac{P_j}{\phi_1}\right]^{1/2} Z + \alpha_{11}Z + \alpha_1 Z^2 + \Omega_1 Z. \tag{A2}$$

Rearranging gives $y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z = \Sigma_{j \neq 1}\alpha_{1j}P_j^{1/2}\phi_1^{-1/2}Z$. Rearranging further gives $\phi_1^{1/2}[y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z] = \Sigma_{j \neq 1}\alpha_{1j}P_j^{1/2}Z$, which then gives: $\phi_1^{1/2} = [Z\Sigma_{j \neq 1}\alpha_{1j}P_j^{1/2}]/[y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z]$. Squaring both sides gives the virtual price ϕ_1:

$$\phi_1 = \left[\frac{Z \sum_{j \neq 1} \alpha_{1j}P_j^{1/2}}{y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z}\right]^2. \tag{A3}$$

The unit rent of y_1 at the margin is:

$$\tau_1 = P_1 - \phi_1 = P_1 - \left[\frac{Z \sum_{j \neq 1} \alpha_{1j}P_j^{1/2}}{y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z}\right]^2. \tag{A4}$$

With quotas y_1 and y_2, the unit rent τ_1 is

$$\tau_1 = P_1 - \phi_1 = P_1 - \left[\frac{\alpha_{12}\phi_2^{1/2}Z + \sum_{j \neq 1,2} \alpha_{1j}P_j^{1/2}Z}{y_1 - \alpha_{11}Z - \alpha_1 Z^2 - \Omega_1 Z}\right]^2. \tag{A5}$$

APPENDIX B: VIRTUAL PRICES AND INVERSE DERIVED DEMAND

Let P be the exogenous price vector of unrationed netput vector X and let Q be the exogenous price vector of the netput vector Y to receive quotas y on outputs or inputs, so that $Y = y$. Z is a vector of quasi-fixed factors with services price vector W. Then virtual prices, ϕ, are defined as an implicit function of y, P, and Z by the restriction that they are those prices that would induce an unregulated firm to produce y: $y = Y[P, \phi, Z]$. See Neary and Roberts (1980) for a formal definition and proof of existence.

The restricted profit function under binding quotas $Y = y$ can be expressed in terms of the unregulated restricted profit function evaluated at ϕ: $\tilde{\pi}[P, Q; y, Z] = \pi[P, \phi; Z] + [Q + \phi]y$. Differentiating with respect to y gives the vector of unit rents (or equivalently, unit implicit tariffs) $\tau[P, Q; y, Z]$ at y: $\tilde{\pi}_y[P, Q; y, Z] = [Q - \phi] = \tau$, where $\tau >$ ($<$) 0 for outputs (inputs) (Fulginiti and Perrin 1993;

Squires 1994). P is the marginal revenue and ϕ is the opportunity cost of production at the margin.

$\pi[P,Q;y,Z]$ provides the vector of marginal valuation functions for exogenous quotas. These functions derived from the production technology indicate the unit quota value required to induce firms to produce on the product transformation frontier supported by Z. Hence, $\pi[P,Q;y,Z]$ provides the firm's vector of input-compensated (net) inverse derived demand functions for quotas y.

Because quota is exogenous, its value at the margin, rather than quantity, adjusts. The matrix $\tilde{\pi}_{yy}[P,Q;y,Z] = \tau_y[P,Q;y,Z]$ states the rates at which the values for y adjust at the margin to induce firms to absorb one more unit of y. $\tau_y[P,Q;y,Z]$ is analogous to the Antonelli matrix of inverse consumer demand (Antonelli 1886; Anderson 1980), is symmetric from Young's Theorem applied to (unregulated) $\pi[P,Q;Z]$, has no restrictions on signs of off-diagonal elements (since there are none on (unregulated) $\pi[P,Q;Z]$), and is negative semi-definite from convexity of (unregulated) $\pi[P,Q;Z]$ in Q (or equivalently, concavity of $\tilde{\pi}[P,Q;y,Z]$ in y).

$\tau_y[P,Q;y,Z] \leqq 0$ for own effects, a counterpart to the law of inverse demand (cf. Anderson 1980). For multiple quotas ($i \neq j$), $\tau_y[P,Q;y,Z] = -\phi_y[P,Q;Z] > (<) 0$ for q-complements (substitutes). $\tilde{\pi}_{yP}[P,Q;y,Z] = \tau_P[P,Q;y,Z] = -\phi_P[P;y,Z] > (<) 0$ for y and X complementary (substitute) outputs. By Young's Theorem, $\tilde{\pi}_{yP}[P,Q;y,Z] = \tilde{\pi}_{Py}[P,Q;y,Z] = -\tilde{X}_y[P,Q;y,Z]$. (The optimal vector of unrationed netputs under a rationing scheme, $-\tilde{X}[P,Q;y,Z] = -X[P,\phi;Z] = \pi_P[P,\phi;Z]$, is identical to the optimal unconstrained vector evaluated at virtual prices; Squires 1994.) $\tau_P[P,Q;y,Z] < 0$ for X a variable input and a normal technology (inputs and outputs are non-regressive; Sakai 1974). $\tilde{\pi}_{yQ}[P,Q;y,Z] = \tau_Q[P,Q;y,Z] = 1$ when $i = j$ and $= 0$ when $i \neq j$. Exploiting Young's Theorem, $\tilde{\pi}_{yQ}[P,Q;y,Z] = \tilde{\pi}_{Qy}[P,Q;y,Z] = y_y$, where $\tilde{\pi}_Q[P,Q;y,Z] = y$ by equation (4) of Squires (1994).

$\tilde{\pi}_Z[P,Q;y,Z] = \pi_Z[P,Q;Z]$ by equation (11) of Fulginiti and Perrin (1993).

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