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Technological and Economic Interrelationships in Hawaii's Troll and Handline Fisheries

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Technological and Economic Interrelationships in Hawaii's Troll and Handline Fisheries

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Abstract.—This paper examines technological and economic interrelationships in Hawaii's troll and handline fisheries. A multiproduct dual revenue function was specified separately for the two fisheries to estimate own-price, cross-price, and effort elasticities of supply for selected species or groups of species. Various aspects of multiproduct cost structure were also analyzed with the information contained in the revenue function model. The null hypothesis of nonjointness in inputs was rejected for the troll fishery but not for the handline fishery. Thus, single-species management may be inappropriate for the former but appropriate for the latter. The acceptance of the input–output separability hypothesis in both fisheries suggests that management of the whole multispecies fishery, rather than regulation of a few key species, may be warranted. Own-price and cross-price elasticity estimates for the troll fishery suggest that the fishers' output supply decisions depend on prices and that pairs of individual species are either substitutes or complements in production. However, in the handline fishery, neither the individual species' own prices nor the prices of other species were found to affect the output supply decisions. Output supplies under both fisheries were positively affected by the effort level. Both fisheries were characterized by cost anticomplementarities, decreasing multiproduct economies of scale, and inelastic cost elasticities.

Pelagic species dominate Hawaii's commercial and recreational fisheries, although bottom fish[1] and lobster[2] are also important. Because of the presence of several fish species in the ocean and the technological structure of fishing vessels, all these fisheries are multispecies in nature. Using different types of vessels (size, tonnage, etc.) and effort (trip length, crew size, gears, etc.), the pelagic fisheries land more than 10 commercially important species for Hawaii's market. Pelagic species are targeted by commercial, recreational, and part-time commercial (expense boat) vessels (Hamilton et al. 1996; Hamilton and Huffman 1997). Large (>35 ft in length) commercial vessels include longline vessels targeting bigeye tuna *Thunnus obesus* and swordfish *Xiphias gladius* and pole-and-line boats targeting skipjack tuna (also known as aku) *Katsuwonus pelamis*. The smaller commercial vessels, as well as recreational and expense boats, include handliners and trollers. Nonchartered trolling vessels are usually trailered boats ranging from 16 to 26 ft long. The handline boats engaged in nearshore fishing are about 23–33 ft long (WPRFMC 1995). Trolling involves towing lures or baited hooks behind a moving vessel, whereas handlining involves dangling baited hooks from a stationary or drifting vessel. A baited hook or hooks in a chummed bundle at the end of the handline is laid against a stone and the line wound around it. The bundle is lowered to the

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[1] Major species caught by Hawaii's bottom fishery are Von Siebold's snapper *Pristipomoides seiboldii*, pink snapper *P. microlepis*, Brigham's snapper *P. zonatus*, squirrelfish snapper *Etelis carbunculus*, Opakapaka *P. filamentosus*, and Seale's grouper (sea bass) *Epinephelus quernus*.

[2] The commercial lobster fishery targets two species, the Hawaiian spiny lobster *Panulirus marginatus* and the common slipper lobster *Scyllarides squammosus*. Small quantities of the green spiny lobster *P. penicillatus* and the ridgeback slipper lobster *S. haanii* are also caught.

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preferred depth (commonly 65–100 ft), then the line is jerked to untie the knot so that the baited hook and chum are released (Boggs and Ito 1993). Handline boats typically operate well within 20–30 mi from shore, but some larger handline and trolling vessels operate further offshore. Charter boats up to about 60 ft in length also operate out of several ports and usually sell their catch.

Landings of important pelagic species in Hawaii include four tuna species (bigeye tuna, yellowfin tuna *T. albacares*, albacore *T. alalunga*, and skipjack tuna), three billfish species (swordfish, striped marlin *Tetrapturus audax*, and blue marlin *Makaira nigricans*), and several miscellaneous pelagic species (dolphin *Coryphaena hippurus*, wahoo *Acanthocybium solandri*, and opah *Lampris guttatus*). The principal species landed by handliners include yellowfin tuna, albacore (nearshore handliners), bigeye tuna (offshore handliners), and dolphin. Dominant species harvested by trollers are yellowfin tuna, dolphin, wahoo, and skipjack tuna. Skipjack tuna boats harvest primarily skipjack tuna.

In 1999, the Hawaii commercial pelagic catch totaled about 36 million pounds, with exvessel revenue of US$59 million (WPRFMC 2001). This represented more than 90% of total commercial catch and value for the state; the remainder came from bottom fish and other fisheries combined. In comparison, the commercial catch was 9–11 million pounds annually for the early and mid-1980s, before the entry of modern longliners associated with the development of local and export markets for fresh tuna, and prior to the advent of new swordfish fishing methods.

In 1999, with regard to total pelagic landings, tuna species accounted for about 45% of total catch and 60% of revenue, while billfish and miscellaneous pelagic species accounted for 55% of catch and 40% of revenue. In terms of landings by fleet, 28 million pounds (79%) were caught by longliners, 3 million pounds (8.3%) by trollers in the main Hawaiian islands (MHI), 2.3 million pounds (6.4%) by MHI handliners, and the remainder by skipjack tuna boats and other gears. The 1991–1998 data showed that troll and handline commercial fisheries harvest about 3–5 million pounds of fish, with an exvessel value of about $5–9 million annually. Of the total troll–handline catch and value, their individual contribution is roughly about 50%, with the handline's contribution rising in recent years, especially that of offshore–distant handlining. The number of commercial trolling activity totaled 21,980 trips, and that of handline activity totaled 5,681 trips in 1999, with both being within their respective long-term averages (WPRFMC 2001).

There have been no significant management concerns with respect to troll and handline fisheries except for their conflicts with longliners during the late 1980s, when the rapid expansion in longline fishing activities adversely affected small boats, including the nearshore trollers and handliners. This problem was resolved in 1990 by prohibiting the longliners from fishing within 50–75 nautical miles of the MHI or within 50 nautical miles of the northwestern Hawaiian islands. Besides the conflicts between the longliners and the trollers and handliners, impacts on endangered marine species and the possibility of localized overfishing were the basis for regulations for the domestic longline fishery in 1990 (Pooley 1990; Boggs and Ito 1993) and subsequent regulations for longliners under the Pelagic Fishery Management Plan (WPRFMC 1994a, b). Shark[3] finning by longliners and other commercial fleets and interactions with protected species[4] continue to be an important public concern (WPRFMC 2001). A recent lawsuit charging that the longline fishery is a threat to the survival of turtle populations has led to an injunction barring swordfish trips in certain waters off the Hawaiian islands.

The restriction on swordfishing may affect the troll and handline fishing activities, but the impact has yet to be observed. Increased tuna fishing by longliners may have an adverse impact on troll and handline fisheries because these fisheries primarily target tunas and other complementary species. This may lead to new conflicts, as well as increased concern regarding overfishing and the impact on protected species by troll and handline activities, thus creating the need for a new regulation tar-

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[3] Hawaii commercial fisheries land numerous shark species, mainly as incidental catch, of which blue shark *Prionace glauca*, mako sharks *Isurus* spp., thresher sharks *Alopias* spp., oceanic whitetip shark *Carcharhinus longimanus*, sandbar shark *C. plumbeus*, and Galapagos shark *C. galapagensis* are important. Of these, blue shark is primarily caught by longliners, while the other species are also caught by trollers and handliners.

[4] Important protected species associated with longline fishing include Hawaiian monk seal *Monachus schauinslandi*, sea turtles (Hawaiian green sea turtle *Chelonia mydas*, leatherback turtle *Dermochelys coriacea*, loggerhead turtle *Caretta caretta*, and hawksbill turtle *Eretmochelys imbricata*), and seabirds (Laysan albatross *Diomedia immutabilis* and black-footed albatross *D. nigripes*).

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geting all three fisheries. This study provides some insights into the likely impacts of regulating handline and troll fisheries.

There has been a growing consensus that fishery policies based on a bioeconomic model of a single or very limited number of species are not appropriate for managing multispecies fisheries. Several studies (Kirkley and Strand 1988; Squires and Kirkley 1991; Thunberg et al. 1995; Diop and Kazmierczak 1996) have indicated that failure to recognize the technical and economic interrelationships among the different species may lead to unintended, negative outcomes for multispecies fisheries management. An understanding of the underlying technological and economic interrelationships among different species is imperative in devising appropriate policies for fishery management.

The main objective of this paper is to examine the technological and economic interrelationships in Hawaii's commercial troll and handline fisheries using a multiproduct dual revenue function approach. This involves estimating supply and effort elasticities and testing for assumptions of input–output separability and nonjointness in inputs. Information presented in this paper can be useful in devising appropriate fishery management policies and in analyzing their impacts.

Conceptual Framework

The behavior of multispecies fishing firms is complicated and not quite established in the literature. Each firm may have different strategies of what to fish, where to fish, how much to fish, when to fish, and how to fish. Fishers may have different behavioral objectives, such as revenue maximization, profit maximization, cost minimization, or maximization of expected utility or satisfaction from a fishing experience. Given their objective, expected prices, and perceptions of stock abundance, fishers choose the gear and effort (input mix), fishing location, trip length, and species composition. This may involve a multistage optimization process (Kirkley and Strand 1988). The size of vessel determines the trip length, the distance of fishing, and crew size (Squires 1987a). Changes in species composition may occur due to changes in several factors, including output and factor prices, stock abundance, and seasonality (Squires 1987b). Due to the distances involved between the port and fishing grounds and trip costs (both in terms of time and fuel), it is rational for the vessel to remain at sea until cumulative catch meets the vessel's storage capacity, provided that it has enough fuel, food supplies, and baits and enough ice to avoid deterioration of fish quality. Fishers may sometime shorten their trips if the weather and market conditions warrant.

Cohorts of different fish species dwelling along a cross section of the ocean profile are harvested by fishers with more or less similar technologies. In other words, several species are targeted in similar waters with similar gears (Thunberg et al. 1995). Regulation of a single species may have a negative effect (or externality) on other species. The degree of externality may vary considerably with the nature of the fish stocks, type of gear used, skill of fishermen, timing of fishing, depth fished, and species targeted (Larson et al. 1996). Bioeconomic models have traditionally formed the basis for regulating multispecies fisheries (Squires 1987b). Under this approach, regulatory authorities often assume independent production functions among the individual species harvested (Kirkley and Strand 1988).

One example of a single-species regulation is the setting of quotas on outputs of individual species. Quotas are often used to regulate production flows of individual firms in multispecies fisheries. It has been widely observed that the quota on individual species can lead to excessive discard of regulated species, technically inefficient production, and unnecessary mortality of nontarget fish species (Kirkley and Strand 1988). With a quota, firms may attempt to reorganize the optimum mix and volume of unregulated species. In the long run, the quota may also induce changes in the quantities of quasi-fixed factors such as vessel size, horsepower, and other capital inputs. Because of an imperfect understanding of the multiproduct production at the firm level and limited empirical information on the firm's product transformation and substitution possibilities, the traditional single-species-based regulations of multispecies fisheries have usually failed (Squires and Kirkley 1991).

Because of widespread uncertainties in technological and economic relationships used in fishery policy analysis, a single, general framework that can be used in the analysis of fishers' decision-making behavior does not exist (Larson et al. 1996). According to Carlson (1973), fishing trips are planned based on perceived species abundance and expected market prices. Once a target species and destination for a trip have been set, all inputs required to make that trip become fixed or sunk costs. On a trip basis, there exist few opportunities to alter the input mix. There are some inputs that may vary with time at sea, but time at sea varies only slightly and the variation is not consistent

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(Kirkley and Strand 1988). Under these conditions, the input mix for a given trip may be viewed as a single composite input. When fishing firms are price takers in output markets, the fishers will attempt to optimize species mix on each trip so as to maximize revenue. Theoretically, when there is a single composite input and marginal cost of additional input is zero, revenue maximization is equivalent to profit maximization (McFadden 1966, 1978; Shephard 1970; Diewert 1974).

The duality theory of production offers an attractive alternative to the traditional bioeconomic approach. Duality is defined as the existence, under appropriate regularity conditions, of ''dual functions'' that embody the same information about the production technologies as is contained in the more familiar primal production functions that represent physical relationships between output and input quantities (Diop and Kazmierczak 1996). 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 production technology when considering a fishery regulation (Squires 1987a). This approach defines a fishing firm's short-run decision-making behavior in terms of revenue maximization subject to a single composite input. Revenue maximization subject to a single fixed input appears to be a reasonable assumption to make for a fishing firm making short-run output decisions (Kirkley and Strand 1988; Thunberg et al. 1995). The revenue function provides input-compensated measures of supply and the respective elasticities[5] (i.e., output supplies and elasticities are conditional on the existing level of fixed input). The duality theory can be applied to examine the technical and economic relationships underlying multiproduct firms, including multispecies fishing firms (Thunberg et al. 1995). Squires (1987b, c) was among the first to apply this approach to fisheries. The theory has widely been applied to agricultural commodities to estimate supply response to changes in prices (Shumway 1983; Taylor and Shonkwiler 1985). Its use in estimating technical and economic relationships and supply responses in the multispecies fishery is rather recent (Thunberg et al. 1995). The essence of this approach is that nonjointness in inputs and separability between outputs and inputs can be parametrically tested (Kirkley and Strand 1988).[6]

Let the generalized revenue function be $R(P, Z)$, where P is a vector of strictly positive output prices and Z is a composite input or effort variable. If $R(P, Z)$ is differentiable in P, a unique revenue-maximizing level of the ith output can be derived as $Q_i(P, Z) = \partial R(P, Z)/\partial P_i$, where ∂ is the symbol for partial differentiation. This forms the basis for estimating own-price and cross-price elasticities of output supplies as well as for testing the assumptions of nonjointness in inputs and input–output separability. These assumptions have important implications for multispecies fishery management.

Separability between inputs and outputs implies that there is no specific interaction between any one output and any one input (Squires 1987a; Kirkley and Strand 1988). Fishers select species on the basis of expected relative prices and prior knowledge, subject to the technological constraints imposed by resource availability and environmental conditions. Changes in relative species prices do not affect production decisions on the optimal combinations of capital, labor, and fuel (Squires 1987a). If the technology is separable between outputs and the fixed input, the dual revenue function is separable in output prices and the composite input. Mathematically, this implies that $R(Z, P) = R(P)Z$. Separability between inputs and outputs implies that total biomass management is possible (e.g., the management of the overall multispecies fish stock rather than individual species) but not necessary. Input–output separability is often assumed in formulating policies involving effort restrictions in multispecies fisheries (Kirkley and Strand 1988).

Jointness in inputs implies that all inputs are required to produce all outputs, whereas nonjoint-

[5] Elasticity is a unit-free measure of a change in one variable in response to a change in another variable. For example, price elasticity of output supply is defined as the percentage change in output supplied for a 1% change in the price of that output.

[6] Separability between inputs and outputs implies no specific interaction between any one output and any one input. The technology can then be specified as a single composite output and single composite input. Only the levels of catch and effort require regulation, and the regulation of species (input) mix does not adversely affect the optimal factor (product) combinations. A joint production process, on the other hand, requires all inputs to produce all outputs. When production is nonjoint in inputs, a separate production function exists for each output or set of outputs. Therefore, each production process can be separately regulated without affecting the production of the other processes because there are no technological or cost tradeoffs between the output of one process and that of another (Squires and Kirkley 1991).

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ness in inputs indicates that a separate production function exists for each output or set of outputs. Nonjointness in inputs implies that decisions about the production of one commodity are independent of decisions about the production of other commodities (Squires 1987a; Kirkley and Strand 1988). In fisheries, nonjointness in inputs implies that each production process can be separately regulated without affecting the production of other species. Nonjointness in inputs over all species implies that the revenue function may be written as $R(Z, P) = \Sigma_i R_i(Z, P_i)$. This further suggests that producers maximize outputs and that the supply of each species is perfectly inelastic. Nonjointness in inputs has been widely assumed in traditional bioeconomic models of multispecies fisheries management (Kirkley and Strand 1988).

The own-price supply elasticities (i.e., changes in output supplies in response to changes in prices of the respective outputs) are expected to be positive. The assumption of revenue maximization implies that fishers will take advantage of changes in relative prices by targeting species that will yield relatively higher revenue. Cross-price elasticities (i.e., changes in output supplies in response to changes in prices of other outputs) can be positive or negative. A positive cross-price elasticity indicates a complementarity in production, either as targeted species or as bycatch: that is, an increase in price of one species would increase production of other species. The negative cross-price elasticity suggests that the two species are substitutes in production (i.e., an increase in price of one species would decrease the harvest of other species) and that effort is allocated among species on the basis of differences in relative prices.

The revenue function also forms the basis for examining various aspects of multiproduct cost structure, including a firm's shadow cost equation, economies of scope, and economies of scale. The firm's total shadow cost C is computed as $C^* = W^* \cdot Z$, where $W^* = \partial R(P, Z)/\partial Z$ is the shadow price or marginal revenue of effort (Z). The shadow cost equation forms the basis for computing multiproduct economies of scope, economies of scale, and cost elasticities. Scope economies provide information on cost savings from product diversification when production is joint in inputs. An important source of scope economies is cost complementarity or cost anticomplementarity. A cost complementarity exists between product i and product j if increased production of Q_j lowers the marginal cost of Q_i. A cost anticomplementarity exists between products i and j if increased production of Q_j raises the marginal cost of Q_i.

Previous Studies

The dual revenue function has mostly been applied to U.S. fisheries in the Atlantic and Pacific oceans for both pelagic and bottom fish species. Species types vary across fishing regions. A few studies have compared the effect of a regulation on the multispecies resource problem. The model specification also varies depending on the purposes of the analysis.

Applying the dual revenue function model of the generalized Leontief form to New England multispecies trawl fishery, Kirkley and Strand (1988) showed that the more commonly advocated forms of stock management, unit stock and biomass, are inappropriate given that managers are concerned with the exploitation of other species. Both hypotheses of nonjointness in inputs and input–output separability were rejected. Own-price elasticities of targeted species (Atlantic cod *Gadus morhua* and yellowtail flounder *Pleuronectes ferrugineus*) were estimated to be positive and significant, while those for incidental or bycatch species (pollock *Pollachius virens* and other flounders) were not significant. The results revealed that restrictions on yellowtail flounder would increase the exploitation of cod, pollock, and haddock *Melanogrammus aeglefinus*.

Using a similar approach, Diop and Kazmierczak (1996) analyzed economic and technical interactions among various species caught by the Mauritanian cephalopod fishery. Both hypotheses of nonjointness in inputs and input–output separability were rejected, suggesting that single-species management would result in negative externalities on other species and that management of the fishery as an aggregate stock would be inappropriate. Own-price elasticities for all species (common octopus *Octopus vulgaris*, common cuttlefish *Sepia officinalis*, and common squid *Loligo vulgaris*) were positive. The authors concluded that the dominance of substitute relationships in the Mauritanian cephalopod fishery would preclude the use of ''key species'' management.

The dual revenue function approach was also used by Thunberg et al. (1995) in analyzing the economic and technical relationships in Florida's nearshore commercial fishery. However, they used the translog functional form instead of the Leontief functional form for the revenue function. Own-price elasticities were found to be positive and mostly significant. Cross-price elasticities were

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also all positive and mostly significant, indicating the complementary relations in production. These findings are consistent with the nonselective nature of the gill-net fishery. The complementary relationship was estimated to be strongest for striped mullet *Mugil cephalus*, which is the dominant species. The authors concluded that effective management of the fishery would be possible through measures designed to regulate the harvest of striped mullet.

Squires (1987c) estimated long-run profit functions obtained from the translog revenue function to determine the technical and economic structure in the New England fishery. The own-price elasticities were inelastic for some species (yellowtail and other flounders) and elastic for others (Atlantic cod and haddock). All cross-price elasticities were estimated to be positive, indicating the jointness in production. Squires and Kirkley (1991) estimated cost functions derived from the generalized Leontief revenue function to examine the firm's short-run response to output quota in California's fishery. The authors concluded that a command-and-control quota on individual firms might be inappropriate for managing sablefish *Anoplopoma fimbria*, as this may result in excessive discard of that species.

Methods

The data.—We used Hawaii Division of Aquatic Resources (HDAR) commercial catch data. The HDAR data contains information on trip-level pounds of fish caught and sold and revenue by species. These data were obtained for the period from 1991 to 1998. Following Pan (1999), troll and handline commercial fleets were defined to include those vessels that had annual exvessel revenue of $5,000 or more. The HDAR data has no information on trip length and other effort variables (such as number of hooks, crew size, etc.) or vessel-specific variables (tonnage, size, etc.). This problem was overcome by aggregating the trip-level data to monthly level and defining effort in terms of the number of trips per month.

Because of differences in species composition, prices, and trip lengths, the HDAR data for the handline fishery were divided into two groups: nearshore and offshore–distant sea. Because the number of observations was insufficient to estimate the revenue function for the distant handliners, the handline results presented here pertain to the nearshore handliners only.

Empirical model.—The revenue function for the analysis of a multispecies fishery can be empirically specified, either in a generalized Leontief flexible functional form as in Kirkley and Strand (1988) and Campbell and Nicholl (1994) or in a translog form as in Thunberg et al. (1995). In this study, the nonhomothetic generalized Leontief revenue function was used. The choice of the generalized Leontief form hinges on the fact that: (1) it allows estimation in terms of output levels rather than revenue shares, as in the translog form, (2) it is linear in its parameters, and (3) it can deal with the nonhomothetic technology. Analyzing the data in the output-level form can be more useful in the management decision process because it provides fishery managers with the type of information they are familiar with (Kirkley and Strand 1988; Diop and Kazmierczak 1996; Bose et al. 2002). Fisheries management and regulation often require information on output levels and their responses to price changes for individual species. The supply elasticities obtained from the estimated output supply equations can be used to calculate changes in output supplies due to changes in output prices.

A dual revenue function in Leontief form is given as

$$R(Z, P) = \sum_i \sum_j \beta_{ij}(P_i P_j)^{1/2} Z + \sum_i \beta_i P_i Z^2 + \sum_i \delta_i P_i X_i Z, \tag{1}$$

where i and j denote fish species, P_i and P_j are output prices for those species, Z is composite effort, X_i and X_j are species-specific stock abundance indices, and β_i, β_{ij}, and δ_i are parameters to be estimated. The species categorization, prices, composite effort (Z), and stock (X) will be described shortly. The specification in equation (1) imposes only a few restrictions on the underlying technology. The one restriction imposed is linear homogeneity in output prices. It also implies jointness in inputs for the controllable factors of production and nonjointness in inputs for the uncontrollable resource stock. Thus, the Leontief form is sufficiently general to permit examination of the underlying economic interrelationships.

Based on Hotelling's Lemma, differentiating the revenue function in equation (1) with respect to prices yields a system of output supply functions as (Varian 1992)

$$Q_i = \sum_{j \neq i} \beta_{ij} \left(\frac{P_j}{P_i}\right)^{1/2} Z + \beta_{ii} Z + \beta_i Z^2 + \delta_i X_i Z. \tag{2}$$

The necessary symmetry condition requires $\beta_{ij} =$

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β_{ji} for $i \neq j$.[7] Separability between inputs and outputs involves the restriction that $\beta_i = 0$. Overall nonjointness in inputs can be examined by testing the restriction that $\beta_{ij} = 0\ \forall\ i \neq j$. Nonjointness in inputs for the kth species can be determined by testing the restriction that $\beta_{kj} = 0\ \forall\ k \neq j$.

The estimated supply equations form the basis for computing own-price supply elasticities for each species and cross-price elasticities among pairs of species. Accordingly, own-price elasticity of the ith fish species (ε_i) could be estimated as follows:

$$\varepsilon_i = \frac{\partial Q_i}{\partial P_i} \cdot \frac{P_i}{Q_i} = -\frac{1}{2Q_i}\left[\sum_{j\neq i} \beta_{ij}\left(\frac{P_j}{P_i}\right)^{1/2} Z\right]. \quad (3)$$

Similarly, the cross-price elasticity of the ith species with respect to the jth species (ε_{ij}) could be computed as

$$\varepsilon_{ij} = \frac{\partial Q_i}{\partial P_j} \cdot \frac{P_j}{Q_i} = \frac{1}{2Q_i}\beta_{ij}\left(\frac{P_j}{P_i}\right)^{1/2} Z. \quad (4)$$

Effort elasticity (i.e., supply response to a change in the amount of composite effort) for the ith species (ε_{iz}) could be computed as follows:

$$\frac{\partial Q_i}{\partial Z} \cdot \frac{Z}{Q_i} = \left[\sum_{j\neq i} \beta_{ij}\left(\frac{P_j}{P_i}\right)^{1/2} + \beta_{ii} + 2\beta_i Z + \delta_i X_i\right] \times \frac{Z}{Q_i}. \quad (5)$$

A supply response to a change in stock conditions can be assessed by computing elasticity with respect to the stock variable for each species as $\varepsilon_{is} = (\partial Q_i/\partial X_i) \cdot (X_i/Q_i)$. The estimated revenue function in equation (1) also forms the basis for deriving the shadow cost equation of effort, $C^* = W^* \cdot Z$, where W^* is derived as follows:

$$W^* = \frac{\partial R(P, Z)}{\partial Z} = \sum_i \sum_j \beta_{ij}(P_i P_j)^{1/2} + 2Z \sum_i \beta_i P_i + \sum_i \delta_i P_i X_i. \quad (6)$$

Measures of cost complementarities are derived from the relationship between the two matrices as (Sakai 1974)

$$\frac{\partial^2 C[W^*, Q(P, Z)]}{\partial Q_i \partial Q_j} = \left[\frac{\partial^2 R(P, Z)}{\partial P_i \partial P_j}\right]^{-1}, \quad (7)$$

where $C[W^*, Q(P, Z)]$ is the equilibrium cost function. Equation (7) is used to examine economies of scope in terms of cost complementarity or anticomplementarity between a pair of outputs.

Following Baumol et al. (1988), the relative degree of economies of scope for product i, $SC_i(Q)$, is computed as follows:

$$SC_i(Q) = \frac{C^*(Q_i) + C^*(Q_{M-i}) - C^*(Q)}{C^*(Q)}, \quad (8)$$

where i and $M - i$ are disjoint product sets such that $M - i$ includes all products except product i and $SC_i(Q)$ is calculated by imposing nonjointness in inputs in the revenue function itself (not the conditional supply equations) and calculating the change in shadow costs.

Similarly, product-specific economy of scale, $S_i(Q)$, is calculated as follows (Baumol et al. 1988):

$$S_i(Q) = \frac{[C^*(Q) - C^*(Q_{M-i})]/Q_i}{\partial C^*(Q)/\partial Q_i} = \frac{AIC_i}{MC_i}, \quad (9)$$

where AIC_i is the average incremental cost and MC_i is the marginal shadow cost for product i. The $S_i(Q)$ is calculated by imposing $P_i = 0$ in the revenue function itself such that the firm no longer produces Q_i.

Multiproduct economies of scale, $S_M(Q)$, is measured by C^*/R, where $C^* = W^* \cdot Z$ in partial economic equilibrium (Laitinen 1980) and R is total revenue. Situations in which $S_M(Q) < 1$, $S_M(Q) > 1$, and $S_M(Q) = 1$ represent decreasing, increasing, and locally constant multiproduct economies of scale (Baumol et al. 1988). Finally, the shadow cost elasticity, which indicates the change in total shadow costs for a change in product i, is calculated as $(\partial C^*/\partial Q_i) \cdot (Q_i/C^*) = (MC_i \cdot Q_i)/(W^* \cdot Z)$.

Species aggregation.—Both trollers and handliners harvest more than 50 targeted and incidental species. Therefore, for revenue function analyses, these species were aggregated to a few species groups in view of the number of parameters to be estimated relative to the number of usable observations. This was done based on pound and revenue shares, prices, and biological characteristics. For trollers, three groups were considered: yellowfin tuna, dolphin and wahoo, and other species. Other species included miscellaneous pelagic and nonpelagic species. Dolphin and wahoo were combined into one group because they have very sim-

[7] The symmetry condition means that the cross-equation relative price coefficients in a system of output supply functions are equal. The dual-based flexible specification imposes the symmetry.

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TABLE 1.—Variables involved in estimating the output supply functions for Hawaii's multispecies troll fishery. A total of 2,311 observations were used in estimating the equations.

Variable	Mean	SD
Output (lb/month)		
Yellowfin tuna	687	1,122
Dolphin and wahoo	436	671
Other species	517	659
Price ($/lb)		
Yellowfin tuna	2.25	0.80
Dolphin and wahoo	2.63	0.68
Other species	1.48	0.58
Effort (number of trips per month)	8.42	5.06
Stock abundance index (1992 = 1.000)		
Yellowfin tuna	0.832	0.076
Dolphin and wahoo	0.923	0.100
Other species	0.924	0.094

ilar prices. Similarly, three groups were considered for nearshore handliners: yellowfin tuna, albacore, and other species (both pelagic and nonpelagic).

Among the groups included in the model, the other species category accounted for the majority of harvest by trollers, followed by dolphin and wahoo, and yellowfin tuna. However, in terms of revenue, the dolphin–wahoo group was most important, followed by yellowfin tuna and other species. In recent years, the share of dolphin and wahoo has increased, while that of other species has decreased in commercial troll landings. For nearshore handliners, in terms of both total catch and revenue, yellowfin tuna was the dominant species.

Thus, the number of species categories included in the analysis was quite limited relative to the number of species landed. On the one hand, all vessels did not harvest all species in every trip, and on the other hand, only observations with complete information on outputs and prices of all species considered in the model were used in estimation, following Kirkley and Strand (1988). Incomplete observations were excluded.[8] Hence, the larger the number of species used in the model, the larger the number of observations unavailable for estimation. At the same time, aggregation also results in loss of information on individual species. Therefore, this tradeoff must be considered in selecting the number of species categories for the analysis and in interpreting the results.

Prices.—In this study, we assumed that fishers' decisions to harvest a given quantity of a particular fish species are based on expected prices rather than on the current prices. We used the one-period lagged (previous month) price as a proxy of expected price. Accordingly, in estimating output supply equations, the current monthly outputs were expressed as functions of prices for the immediate previous month, composite effort, and stock variable.

Effort variable.—Neither effort information (trip length, number of hooks, etc.) nor vessel-specific information (tonnage, size, etc.) were available in the HDAR data for trollers and handliners. This problem was overcome by aggregating the trip-level data to monthly levels and then defining effort in terms of the number of trips per month. Typically, a troll or handline trip is usually a 1-d trip. Thunberg et al. (1995) also defined effort in terms of the number of trips per month.

Stock variable.—Catch per unit of effort (CPUE) is usually the only available information on stock abundance. Total pounds landed for each species and total effort (i.e., the number of trips) during the year were used to reflect species-specific stock abundance measures. In this study, the stock variables (X) in the revenue function model were expressed in terms of indices, as described below.

First, for each species category, the CPUE measure was computed as total pounds landed divided by the total number of trips during the year for the entire fishery. The CPUE measure for each year was then indexed by using 1992 as a reference year. Thus, a value greater than 1.0 for a given year reflects a better stock situation for that year relative to 1992, and a value less than 1.0 indicates

[8] The numbers of complete, aggregated monthly observations used in the analysis of nearshore handline and troll fisheries were 762 and 2,311, respectively. The complete observations represented 15% and 16% of the total monthly aggregated observations for the handline and troll fisheries, respectively. A significant proportion of observations had to be discarded to avoid the problems of zero outputs in estimating output supply equations.

TABLE 2.—Variables involved in estimating the output supply functions for Hawaii's multispecies nearshore handline fishery. A total of 762 observations used in estimating the handline supply equations.

Variable	Mean	SD
Output (lb/month)		
Yellowfin tuna	2,929	2,855
Albacore	1,111	1,265
Other species	284	454
Price ($/lb)		
Yellowfin tuna	2.37	0.67
Albacore	1.10	0.34
Other species	2.02	0.67
Effort (number of trips per month)	9.47	5.51
Stock abundance index (1992 = 1.000)		
Yellowfin tuna	0.639	0.234
Albacore	2.000	0.638
Other species	1.256	0.273

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a worse stock situation relative to 1992. The potential endogenity problem in using CPUE as a proxy of the stock variable would have been minimized, as these stock indices were annual aggregate estimates for the entire fishery, while the dependent variables in the supply equations were total monthly landings for individual fishers. Alternative measures of stock level, such as seasonal and yearly dummies, were also tried, but the annual species-specific stock indices produced more plausible results.

In previous studies, the effect of stock abundance or biomass was usually captured by including seasonal or yearly dummies in the revenue function. Using the stock index is preferred to using time dummies because fewer parameters require estimation, especially when the data come from several years, as in the present study. Use of the stock index also allows us to examine a supply response to changes in stock situations for each species.

Results

The variables (outputs, prices, composite effort, and stock indices) involved in estimating the output supply equations for the troll and handline fisheries are summarized in Tables 1 and 2, respectively.

Parameter Estimates

The systems of output supply functions obtained from the generalized Leontief revenue functions were estimated using Zellner's seemingly unrelated regression estimation technique (Greene 2000). The system-weighted R^2 values were 0.30 and 0.09 for the handline and troll fisheries, respectively.[9]

The parameter estimates for the troll output supply equations for three groups (yellowfin tuna, dolphin and wahoo, and other species) are presented in Table 3. Only one set of cross-price coefficients is presented in the table because of the symmetry condition. All price-related coefficient estimates were significant at the 0.05 level. The supply of yellowfin tuna was negatively related to prices of dolphin and wahoo and other species, while the relationship between dolphin and wahoo and other species was positive. As expected, the stock coefficients were positive for all three groups, in-

[9] A dual-based revenue function should satisfy the regularity conditions (homogeneity, symmetry, monotonicity, convexity, and concavity). It should be noted that, as in most previous studies on application of a dual revenue function to multispecies fisheries, we did not conduct the formal tests of underlying regularity conditions of the dual-based revenue function, except for examining the convexity and testing the symmetry restriction on individual coefficients in both troll and handline fisheries. A cursory look at parameter and elasticity estimates suggests that several of these conditions appear to be satisfied, especially in the revenue function for the troll fishery. Homogeneity does not need to be tested, as the generalized Leontief function implies linear homogeneity. Concavity appears to be satisfied at the mean level for the troll fishery, but may not be satisfied for the handline fishery. However, one cannot conclude that concavity is globally satisfied unless concavity is further examined. Convexity was examined and the substitution matrix was positive definite for the troll fishery and negative definite for the handline fishery. In both troll and handline fisheries, it appears that the data fit better when symmetry was imposed, as two of the three coefficients were significant with symmetry imposed.

TABLE 3.—Parameter estimates (SEs in parentheses) for output supply functions for Hawaii's multispecies troll fishery. Asterisks indicate significance at the 0.05 level.

Species	Yellowfin tuna	Dolphin and wahoo	Other species	Effort	Effort squared	Stock index
Yellowfin tuna		−21.991** (6.076)	−12.984** (4.734)	36.536 (26.943)	1.551** (0.287)	20.878 (29.119)
Dolphin and wahoo			11.585** (4.804)	−6.425 (14.436)	−0.956** (0.173)	72.809** (13.164)
Other species				−21.859 (15.557)	−0.559** (0.166)	82.430** (14.685)

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dicating a positive relationship between the levels of catch and stock abundance, although the coefficient in the yellowfin tuna equation was not significant. The coefficients associated with effort and effort-squared terms were mixed and are therefore better explained in terms of elasticities of supplies with respect to effort.

Similarly, the parameter estimates of output supply equations for three groups (yellowfin tuna, albacore, and other species) for the nearshore handline fishery are presented in Table 4. Unlike the troll fishery, none of the cross-price coefficients for the handline fishery was significant at the 0.05 level. However, most of the effort-related coefficients had expected signs. As expected, the coefficients associated with stock abundance were positive for all three species categories.

Tests of Hypotheses

The hypothesis for nonjointness in inputs was tested for all groups jointly as well as for each group separately. The hypothesis of nonjointness in inputs was rejected for the troll fishery for all three groups jointly as well as individually (Table 5). However, the hypothesis of input–output separability was not rejected for the troll fishery. For the nearshore handline fishery, neither of the hypotheses were rejected.[10] Thus, the single-species management would be inappropriate for trolling but appropriate for nearshore handlining. According to input–output separability tests, both of these fisheries should be managed as a whole rather than on the basis of individual species.

Elasticity Estimates

The coefficient estimates presented were used to compute the own-price, cross-price, effort, and stock elasticities of output supplies for the troll and handline fisheries (Tables 3, 4). The elasticity estimates were evaluated at the mean values of relevant variables, and their standard errors were derived with the variance–covariance structure of the relevant estimates.

Price, effort, and stock elasticities for trollers are presented in Table 6. As expected, own-price elasticities were estimated to be positive for all three groups considered. These estimates were significant at the 0.05 level for yellowfin tuna and at the 0.10 level for dolphin and wahoo. All cross-price elasticities were significant at the 0.05 level. The cross-price elasticities between yellowfin tuna and dolphin–wahoo or other species were negative, suggesting that yellowfin tuna is a production substitute for both species groups. However, a decline in outputs of dolphin and wahoo and other species due to an increase in price of yellowfin tuna would be larger than the decline in yellowfin tuna output due to an increase in price of the other two groups. Dolphin and wahoo and other species were found to be complementary in production. As expected, effort elasticities were estimated to be positive and highly significant for all three groups. Effort elasticities for the three species categories were of fairly comparable magnitude. Measures of stock

[10] It would also be interesting to conduct tests of weak separability to see if some outputs are weakly separable. This would not only provide additional insights into alternative aggregation mechanisms but also may have potentially important implications for fishery management. However, we were unable to implement such tests because of limited observations with nonzero outputs if different subsets of outputs were considered.

TABLE 4.—Parameter estimates (SEs in parentheses) for output supply functions for Hawaii's nearshore handline fishery. Asterisks indicate significance at the 0.01 (***), 0.05 (**), and 0.10 (*) levels.

Species	Yellowfin tuna	Albacore	Other species	Effort	Effort squared	Stock index
Yellowfin tuna		17.576 (17.215)	10.626 (7.687)	128.711** (50.500)	−7.062*** (1.780)	475.775*** (28.429)
Albacore			−2.045 (9.691)	28.114 (35.634)	−1.863* (1.018)	38.437*** (5.936)
Other species				4.364 (13.634)	−0.656 (0.400)	11.761** (5.521)

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TABLE 5.—Tests of hypotheses of nonjointness in inputs and separability between inputs and outputs in Hawaii's troll and handline fisheries. See text for an explanation of symbols.

Hypothesis	F-statistic	df	Critical value ($\alpha = 0.05$)	Decision
Troll fishery				
Nonjointness in inputs ($\beta_{ij} = 0 \ \forall \ i \neq j$)				
Overall	7.52	3, 6,918	2.60	Reject null
Yellowfin tuna	10.98	2, 6,918	3.00	Reject null
Dolphin and wahoo	8.91	2, 6,918	3.00	Reject null
Other species	4.48	2, 6,918	3.00	Reject null
Input–output separability ($\beta_i = 0$)	1.35	3, 6,918	2.60	Accept null
Handline fishery				
Nonjointness in inputs ($\beta_{ij} = 0 \ \forall \ i \neq j$)				
Overall	1.21	3, 2,271	2.60	Accept null
Yellowfin tuna	1.28	2, 2,271	3.00	Accept null
Albacore	0.52	2, 2,271	3.00	Accept null
Other species	1.34	2, 2,271	3.00	Accept null
Input–output separability ($\beta_i = 0$)	2.25	3, 2,271	2.60	Accept null

elasticity were positive for all three species groups and significant for dolphin and wahoo and other species.

Estimates of own-price, cross-price, effort, and stock elasticities for nearshore handliners are given in Table 7. None of the own-price and cross-price elasticities was significant at the 0.05 level. Effort elasticities were positive and significant ($P < 0.01$) for all species groups. Estimates of stock elasticities were also found to be positive and significant for all three groups. Both the effort and stock elasticities were highly elastic for the yellowfin tuna.

Multiproduct Shadow Cost Structure

All product pairs exhibited cost anticomplementarities, meaning that increased production of one species would increase the marginal cost of other species. The shadow price of effort (i.e., trip) was estimated as $255 for trollers and $896 for handliners, with total shadow trip costs of $2,151 and $8,488, respectively (Table 8). Multiproduct economies of scale were estimated as 0.622 for trollers and 0.971 for handliners, implying decreasing returns to scale for both fisheries.

Average incremental costs were highest for dolphin and wahoo for trollers and yellowfin tuna for handliners. Negative shadow economies of scope indicated that joint production of all three species groups tends to increase costs in trolling relative to individual production of those same groups (Table 9). However, as indicated by positive shadow economies of scope, the nearshore handliners would experience cost savings by producing the three groups jointly (Table 10). For all three groups in trolling, product-specific economies of scale were estimated to be less than 1.0, indicating decreasing returns to scale. In the case of handlining, results indicated decreasing returns to scale for albacore and other species, and constant returns to scale for yellowfin tuna. Costs were found to be output inelastic for all species groups in both troll and handline fisheries.

Discussion

The main purpose of this study was to characterize technical and economic interrelationships among species harvested by Hawaii's commercial troll and handline fisheries. The 1991–1998 trip-level pounds sold, revenues, and prices obtained from HDAR sales reports were analyzed using the dual revenue function approach. Assuming reve-

TABLE 6.—Price, effort, and stock elasticities (SEs in parentheses) for Hawaii's multispecies troll fishery. Asterisks indicate significance at the 0.05 (**) and 0.10 (*) levels.

Species	Price elasticity with respect to			Effort elasticity	Stock elasticity
	Yellowfin tuna	Dolphin and wahoo	Other species		
Yellowfin tuna	0.210** (0.045)	−0.145** (0.040)	−0.065** (0.024)	0.562** (0.063)	0.215 (0.300)
Dolphin and wahoo	−0.196** (0.054)	0.112* (0.062)	0.084** (0.035)	0.662** (0.060)	1.322** (0.239)
Other species	−0.130** (0.042)	0.126** (0.031)	0.005 (0.038)	0.759** (0.061)	1.236** (0.220)

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TABLE 7.—Price, effort, and stock elasticities (SEs in parentheses) for Hawaii's nearshore handline fishery. Asterisks denote statistical significance at the 0.01 (***) and 0.05 (**) levels.

Species	Price elasticity with respect to			Effort elasticity	Stock elasticity
	Yellowfin tuna	Albacore	Other species		
Yellowfin tuna	−0.035 (0.024)	0.019 (0.019)	0.015 (0.011)	3.702*** (0.165)	3.648*** (0.218)
Albacore	0.109 (0.108)	−0.098 (0.109)	−0.011 (0.056)	0.791*** (0.077)	0.656*** (0.101)
Other species	0.191 (0.139)	−0.025 (0.119)	−0.166 (0.111)	0.558*** (0.118)	0.493** (0.231)

nue maximization as the behavioral objective of multispecies fishing firms, the monthly output was specified to be a function of monthly lagged prices, effort (number of trips per month), and the annual species-specific stock indices. Species were aggregated to three groups for each fishery. These included yellowfin tuna, dolphin and wahoo, and other species for trollers; and yellowfin, albacore, and other species for handliners. Besides testing hypotheses of nonjointness in inputs and input–output separability, output supply elasticities (own-price, cross-price, effort, and stock), effort elasticities with respect to output prices, and multiproduct shadow cost structure (multiproduct economies of scope and scale, product-specific economies of scope and scale, and cost elasticities) were examined.

The hypothesis of nonjointness in inputs was rejected for the troll fishery, indicating a joint production process. From the fishery management perspective, this finding indicates that the exploitation of one species would affect the exploitation of other species. In other words, the traditional single-species regulation would be inappropriate in managing the troll fishery. Because of jointness in production, regulating one species would affect the harvest of other species. For example, there is a significant substitute relationship of yellowfin tuna with dolphin–wahoo and other species, implying that a restriction on harvest of yellowfin tuna would result in the increased exploitation of the other two species groups. However, the relationship between dolphin–wahoo and other species is one of complementarity. In this case, output restrictions on dolphin and wahoo would result in the reduction of harvest of other species. On the other hand, the hypothesis of nonjointness in inputs was not rejected for the handline fishery, indicating that the single-species regulation may be appropriate in managing this fishery. Such a finding is consistent with the selective nature of the handline gear. Therefore, the estimated cross-price elasticities provide substantial evidence of the need for fishery managers to consider technical and economic interactions, which can guide policy implications of a specific fishery policy.

The hypothesis of input–output separability was accepted in both fisheries. This suggests that each of these fisheries could be managed as a whole rather than on the basis of individual species. The finding is also consistent with Hawaii's fishery management in the past through area closure, where the primary focus has been to minimize the gear conflicts between longliners, trollers, and handliners and to minimize impacts on protected species rather than managing individual fish species.

The tests of hypotheses of nonjointness in inputs and input–output separability for Hawaii's troll and handline pelagic fisheries produced quite different results compared with studies in the literature for other fisheries. While both hypotheses were rejected for other fisheries in previous studies, the hypothesis of input–output separability was not rejected in either the troll or handline fisheries. Furthermore, for handliners, the hypothesis of nonjointness in inputs was also not rejected. Species-specific management regulations can thus be devised for the handline fishery.

Outputs were found to be fairly positively price responsive in the troll fishery, particularly for the dominant species, such as yellowfin tuna. How-

TABLE 8.—Multiproduct shadow cost structure and economies of scale for Hawaii's troll and nearshore handline fisheries.

Fishery	Shadow price of effort (W^*; $)	Effort (Z)	Total shadow cost of effort/trip ($C^* = W \cdot Z$; $)	Total revenue (R; $/trip)	Multiproduct economy of scale ($S_M[Q] = C^*/R$)
Troll	255.41	8.42	2,151	3,459	0.622
Handline	895.9	9.475	8,488	8,742	0.971

TABLE 9.—Economies of scope, product-specific economies of scope, and cost elasticities for Hawaii's multispecies troll fishery.

Species	Incremental cost ($/trip)	Average incremental cost ($)	Degree of shadow economy of scope	Product-specific economy of scale	Cost elasticity
Yellowfin tuna	887	1.291	−0.005	0.574	0.718
Dolphin and wahoo	732	1.679	−0.004	0.638	0.533
Other species	552	1.068	−0.005	0.721	0.356

ever, for the handline fishery, outputs were not responsive to their respective prices. In view of the selective nature of handline gear, this result appears to be somewhat ambiguous, suggesting the need for further research on harvest decisions of handliners. As expected, both effort and stock elasticities of output supplies were positive and significant in almost all cases. Effort elasticities indicated the possibility of managing these fisheries through effort regulation, such as limiting the number of trips.

The analysis of multiproduct shadow cost structure showed decreasing returns to scale in both the troll and handline fisheries. Between the two fisheries, handliners appeared to be more scale efficient, perhaps due to their advantage in controlling their output mix. For trollers, achieving scale efficiency may be difficult due to incidental bycatch of nontarget species. Cost anticomplementarities were dominant in both fisheries. Product-specific economies of scale also revealed decreasing returns to scale for most species groups. Although the production was characterized by jointness in inputs for the troll fishery based on degree of shadow economies of scope, joint production did not reveal any cost advantages in these fisheries. Perhaps this may again be attributed to fishers' limited ability to choose an optimal output mix due to incidental catch, which is not easily controllable by fishers.

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TABLE 10.—Economies of scope, product-specific economies of scope, and cost elasticities for Hawaii's nearshore handline fishery.

Species	Incremental cost ($/trip)	Average incremental cost ($)	Degree of shadow economy of scope	Product-specific economy of scale	Cost elasticity
Yellowfin tuna	7,082	2.418	0.036	1.020	0.818
Albacore	710	0.639	0.035	0.580	0.144
Other species	−50	−0.174	0.045	−0.086	0.068

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