Marine Resource Economics, Volume 18, pp. 167–193
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0738-1360/00 $3.00 + .00

Analyzing Technical and Economic Interrelationships in Hawaii's Longline Fishery

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Abstract *This paper provides an analysis of technical and economic interrelationships among species harvested in Hawaii's pelagic longline fishery. The results indicate that this multispecies fishery is characterized by a joint production process, meaning that the regulation of one species would affect the harvest of other species. It implies that a single species regulation may not be appropriate in managing the longline fishery. Estimates of own-price output supply elasticities suggest that fisher's decisions on the amounts of each species harvested are independent of own expected prices. However, as evidenced by the estimates of cross-price elasticities, there are a number of significant technical-economic interactions among species. Failing to reject the null hypothesis of input-output separability suggests that management of the entire fishery as a whole by partial area/seasonal closure or by a 'limited entry' system as in the past is justified instead of regulating a few key species.*

Key words Multispecies, pelagic longline fishery, dual revenue function, joint production, input-output separability.

JEL Classification Codes Q21, Q22.

Introduction

Management and regulation of multi-species marine fisheries is frequently complicated by unknown technical and economic interrelationships among different species (outputs). For example, a quota or output restriction on one species may result in increased exploitation of other species (Kirkley and Strand 1988). There has been a growing consensus that fishery policies based on the bioeconomic model of a single species are not appropriate for managing multispecies fisheries. Several stud-

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This research is funded by Cooperative Agreement Number NA37RJ0199 between the Joint Institute of Marine and Atmospheric Research (JIMAR), University of Hawaii, and the National Oceanic and Atmospheric Administration (NOAA). The authors would like to thank Sam Pooley, National Marine Fisheries Service (NMFS), Honolulu Laboratory, for making the datasets available and for providing constructive comments on earlier drafts. The authors are also thankful to three anonymous reviewers and an associate editor for their constructive comments and suggestions to improve the paper. However, the authors are responsible for any remaining errors and weaknesses in the paper.

ies (Kirkley and Strand 1988; Squires and Kirkley 1991; Thunberg, Bresnyan, and Adams 1995; Diop and Kazmierczak 1996) have indicated that failure to recognize the technical and economic interrelationships among different species may lead to unintended, negative outcomes for multispecies fisheries management. Therefore, it is imperative to understand the underlying technical and economic interrelationships among different species to devise appropriate policies for fishery management. Information about species interaction is critical to Hawaii's pelagic fisheries in the context of a recent harvest ban of swordfish, *Xiphias gladius,* a major species targeted by longliners.

The main objective of this paper is to analyze the technical and economic interrelationships among species harvested by Hawaii's longline fishery during 1991–98 using a multiproduct dual revenue function approach. It involves estimating supply, effort and stock elasticities, and testing for hypotheses of nonjointness-in-inputs and input-output separability. Information presented here can be useful in devising appropriate fishery management policies and analyzing their technical and economic impacts.

Longline Fishery in Hawaii

Pelagic species dominate Hawaii's commercial and recreational fisheries, although bottomfish and lobster are also important. Landings of important pelagic species by Hawaii's fisheries include four tuna species (bigeye tuna, *Thunnus obesus;* yellowfin, *T. albacares;* albacore, *T. alalunga;* and skipjack/aku), three billfish species (swordfish; striped marlin, *Tetrapterus audax*; and blue marlin, *Makaira mazara*) and several miscellaneous pelagic species (mahimahi, *Coryphaena hippurus;* wahoo/ono, *Acanthocybium solandri;* aku, *Katsuwonus pelamis;* and moonfish/opah, *Lampris guttatus*). These species are targeted by commercial, recreational, and part-time commercial (expense boat) vessels (Hamilton, Curtis, and Travis 1996; Hamilton and Huffman 1997).

Hawaii's commercial pelagic catch totaled about 36 million pounds with ex-vessel revenue of $59 million in 1999 (WPRFMC 2001). The longline fishery represented about 90% of total commercial catch and value for the state. The remainder came from bottomfish and other fisheries. In comparison, the commercial catch was 9 to11 million pounds annually for the early- and mid-1980s. In 1999, tuna species accounted for 45% of total commercial pelagic catch and 60% of total revenue, while billfish and miscellaneous pelagic species accounted for the rest. In terms of total landings by fleet, 28 million pounds (79%) of the total commercial pelagic catch was caught by longliners, 3 million pounds (8.3%) by trollers, 2.3 million pounds (6.4%) by handliners, and the remainder came from aku and other gears. Landings of each fleet feature multiple species.

Bigeye tuna has been a major target species since the 1950s. Swordfish was a minor species until the 1990s when it became the major target species with the entry of modern longline vessels targeting swordfish (Curran, Boggs, and He 1996; Dollar 1992). Swordfish and bigeye tuna account for most of the longline catch. However, longliners also capture a significant amount of other pelagic species, such as yellowfin tuna, albacore tuna, striped marlin, blue marlin, and some sharks. In 1999, the longline fleet accounted for 99% of Hawaii's total commercial swordfish catch, 97% of bigeye tuna, 89% of striped marlin, 79% of albacore tuna, 56% of blue marlin, and 100% of sharks (WPRFMC 2001).

Hawaii's longline fleet includes several older wooden longliners, a few wood and fiberglass vessels, and many newer steel longliners that were previously engaged in the fishery off the US mainland. The older vessels measure 43–70 feet in length and are capable of taking two-week trips, while the more modern vessels measure 70–100 feet and can travel for 2–3 months. The newer vessels are often outfitted with water and ice-making machines and modern electronic equipment for navigation, communications, and locating fish (WPRFMC 1995a). In a relatively short time span, the longline fishery has grown to be the largest and most prominent commercial fishery in Hawaii. The number of active longline vessels almost quadrupled, from 37 vessels in 1987 to a high of 141 vessels in 1991. This number then leveled off at about 120 vessels from 1992 through 1994, declined slightly to 103 vessels in 1996, and increased to 125 vessels in 2000 (Ito and Machado 2001).

Longlining allows a single vessel to spread effort over a large area to harvest fish that are not concentrated enough to be caught by other fishing methods. Longline fishing gear consists of a monofilament main line strung horizontally across 1-100 km of sea, supported by vertical float lines connected to surface floats at regular intervals. Descending from the main line are branch lines, each ending in a single, baited hook. The main line droops in a curve from one float line to the next and bears from two to 25 branch lines between floats. One set of longline gear can consist of thousands of hooks clipped to the main line extending across several miles of ocean. Fishing depth depends on the length of the float lines and branch lines, the sag in the main line, and the position of the branch lines. Fishing depth affects the efficiency with which different species are captured. One longline set is made per fishing day, and the deployment and retrieval of the lines may take up to 24 hours (Boggs and Ito 1993).

The National Marine Fishery Services (NMFS) Honolulu Laboratory classifies longline fishing trips into one of the three trip categories: swordfish trip, tuna trip, and mixed trip, based on interviews, fishing destination, input use, time of set, catch composition, and species targeted (Curtis 1999).[1] It was observed that some vessels choose to specialize either in bigeye tuna or swordfish, while others harvest both during a trip. Each trip strategy involves a different production technology, such as timing of laying out sets, depth, and number of hooks and light sticks.[2]

Hawaii longliners often sell their fresh tuna at the auction to both local and export wholesalers. The auction price is determined by a combination of factors, such as the buyers' assessment of quality, market demand, and current supply of fish. The swordfish catch, on the other hand, is typically sold directly to export wholesalers who ship it by air to the US mainland, Japan, and Europe (WPFRMC 1995a, 1995b).

The most significant change in Hawaii's longline fishery over recent years has been the shift of effort from swordfish trips to tuna trips. For example, the number of swordfish trips declined from 292 in 1991 to just 84 in 1998. On the other hand, the number of tuna trips increased from 556 to 760 over the same period (Ito and Machado 2001). Conflicts between longliners and the trollers and handliners, concern over impacts on endangered species, and the possibility of localized

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[1] The timing and configuration of a set used in the mixed trip is similar to that used in the swordfish trip except that the mixed set uses fewer light sticks and slightly more hooks, enabling the mixed set to target both bigeye tuna and swordfish. The mixed trip does not involve altering a set or switching sets designed to target bigeye tuna or swordfish during a trip. In 98% of trips during 1991–98, it was observed that fishers select only one type of set; *i.e.*, swordfish set, tuna set, or mixed set during a trip.

[2] The length of the main line in a tuna set is about 20–25 miles compared to 35–45 miles in swordfish and mixed sets. The tuna set is laid out in the morning and hauled in the evening, while swordfish and mixed sets are laid out in the evening and hauled in the morning (Curtis 1999). It is evident from the 1991–98 logbook records that, on average, tuna sets use more hooks per set compared to swordfish and mixed sets; *i.e.*, 1,441 hooks/set in tuna sets vs. 815 and 876 hooks/set in swordfish and mixed sets, respectively. Swordfish sets differ with mixed sets in terms of the number of light sticks; *i.e.*, 485 light sticks/set in swordfish sets vs. 225 light sticks/set in mixed sets.

overfishing were the basis for developing regulations in 1990 (Pooley 1990; Boggs and Ito 1993) and subsequent regulations under the Pelagic Fishery Management Plan (WPRFMC 1994a and 1994b). Shark finning by longliners and other commercial fleets and interactions with protective species (marine turtles and sea birds) continue to be of important concern (WPRFMC 2001). A recent lawsuit charging that the longline swordfishing is a threat to survival of turtle populations has led to an injunction barring swordfish trips in certain waters off the Hawaiian Islands. This has forced swordfish vessels either to leave Hawaii or to switch to tuna fishing. About one-third of the longline vessels left to California after the ban on the swordfish harvest came into effect in summer 2000. The remaining vessels are now involved in longline tuna fishing.

Conceptual Framework

The behavior of multispecies fishing firms is complicated and not quite established in the literature. Each firm may have different strategies regarding what to fish, where to fish, how much to fish, when to fish, and how to fish. Fishermen may have different behavioral objectives, such as revenue maximization, profit maximization, cost minimization, or maximization of expected utility. Given their objective, expected prices, and perceived stock abundance, fishers choose the gear, effort (input mix), and fishing location, which ultimately determines species composition. This may involve a multistage optimization process (Kirkley and Strand 1988). The vessel size determines the trip length, trip distance, 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 associated trip costs (both in terms of time and fuel), it is rational for the fisher to keep his vessel at sea until cumulative catch meets its storage capacity, provided that it has enough fuel, food supplies, baits, and ice to avoid deterioration of fish quality. Fishers may sometimes shorten their trips if the weather and market conditions warrant.

Cohorts of different fish species dwelling along a cross-sect of the ocean profile are harvested by fishers using more or less similar technologies. In other words, several species are targeted in similar waters using similar gears (Thunberg, Bresnyan, and Adams 1995). The regulation of a single species may result in a negative externality on other species. The degree of such externality may vary considerably with stock abundance, type of gear used, skill of fishermen, timing of fishing, depth fished, and species targeted (Larson, House, and Terry 1996). The single-species bioeconomic models have traditionally formed the basis for regulating multispecies fisheries (Squires 1987b). Under this approach, regulatory authorities often assume independent production functions among individual species landed (Kirkley and Strand 1988).

One example of single-species regulation is to set quotas on outputs of individual species. Quotas are often used to regulate the harvest of individual species in multispecies fisheries. It has been widely observed that the quotas on individual species can lead to excess discard of regulated species, technically inefficient production, and unnecessary fish mortality of unintended species (Squires and Kirkley 1991). With individual transferable quotas, fishers may attempt to reorganize the optimum mix and volume of unregulated species. In the long-run, it may also induce changes in the quantities of quasi-fixed factors. 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).

The duality theory of production offers an attractive alternative to the traditional bioeconomic approach in analyzing economic and technical structure in multispecies fisheries. Duality is defined as the existence, under appropriate regularity conditions of "dual functions" that embody the same information about the production technologies as contained in the more familiar primal functions (Diop and Kazmierczak 1996). 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). A dual revenue function can be used to determine the technical and economic interrelationships among species in a multispecies fishery. Once target species and destination for a trip have been set, all inputs required to make that trip become fixed (*i.e.*, costs are sunk). Under these conditions, the input mix for a given trip may be viewed as a single composite input. On a trip basis, there exist limited opportunities to alter the input mix. When fishing firms are price takers in output markets, a fisher will attempt to optimize species mix on each trip to maximize revenue (Kirkley and Strand 1988).

The dual revenue framework does not focus on steady-state levels of the variables. Rather it offers the more immediate and detailed knowledge of the individual firm's production technology when considering a fishery regulation (Squires 1987b). This approach defines the 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, Bresnyan, and Adams 1995). The duality theory can be applied to examine the technical and economic relationships underlying multiproduct firms, including multispecies fishing firms (Thunberg, Bresnyan, and Adams 1995). Squires (1987a,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 a recent one (Thunberg, Bresnyan, and Adams 1995). The essence of this approach is that the assumptions of nonjointness-in-inputs and separability between outputs and inputs can be parametrically tested (Kirkley and Strand 1988).

The general revenue function is specified as:

$$R(P, Z) = \max\left\{P \quad Q : Q \quad Q(Z), P > 0\right\}, \tag{1}$$

where $R(P,Z)$ is a revenue function, P is a vector of strictly positive output prices, and Z is a composite of input or an effort variable. If $R(P,Z)$ is differentiable in P, a unique revenue-maximizing output vector exists with typical i^{th} element being as follows:

$$Q_i(P, Z) = \frac{\partial R(P, Z)}{\partial P_i}. \tag{2}$$

Equation (2) forms the basis for estimating own- 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 (Kirkley and Strand 1988; Squires 1987b). Fishers' decisions on choice of target species are based on their expected relative prices and prior knowledge subject to the technical constraints imposed by resource availability and environmental conditions. Changes in relative species prices do not have an effect on the optimal combinations of capital, labor, and fuel (Squires 1987b). 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 $R(Z,P) = R(P)Z$. This requires the marginal rate of transformation for all output pairs be independent of all factor intensities (Hall 1973). The technology can then be specified up to a single composite output and single composite input. In such a case, only the aggregate levels of catch and effort require regulation, and regulation of species (input) mix does not adversely affect the optimal factor (product) combinations (Squires and Kirkley 1991). It also implies that total biomass management is possible (*e.g.*, the management of overall fish stock rather than individual species). 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, while nonjointness-in-inputs implies a separate production function for each output or set of outputs. It implies that decisions about production of one commodity are independent of decisions about the production of other commodities (Squires 1987b; Kirkley and Strand 1988). Therefore, each production process can be separately regulated without affecting production of the other processes because there are no technological or cost tradeoffs between the output of one process and that of another (Squires and Kirkley 1991). 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 implies that producers maximize harvests, and 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 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 can be positive or negative. A positive cross-price elasticity indicates a complementarity in production either as targeted species or as bycatch; *i.e.*, an increase in price of one species will increase production of other species. The negative cross-price elasticity suggests that the two species are substitutes in production and that effort is allocated among species on the basis of differences in relative prices; *i.e.*, an increase in price of one species will decrease the production of other species.

The revenue function in equation (1) also forms the basis to examine various aspects of multiproduct cost structure, including the firm's shadow cost economies of scope and economies of scale. The firm's total shadow cost is computed as: $C^* = W^* \cdot Z$, where $W^* = \partial R(P, Z)/\partial Z$, the shadow price or marginal revenue of effort (Z). 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 anti-complementarity. A cost complementarity (anti-complementarity) exists between product i and product j if increased production of Q_j lowers (raises) the marginal cost of Q_i. Measures of cost complementarities are derived from the relationship between the two matrices as (Sakai 1974):

$$\left[\frac{\partial^2 C[W^*, Q(P, Z)]}{\partial Q_i \partial Q_j}\right] = \left[\frac{\partial^2 R[P, Z]}{\partial P_i \partial P_j}\right]^{-1}, \qquad (3)$$

where $C[W,Q(P,Z)]$ is the equilibrium cost function, which forms the basis for computing multiproduct economies of scope, economies of scale, and cost elasticities.

Previous Studies

The dual revenue function has mostly been applied to fisheries in the Atlantic and Pacific Oceans involving both bottomfish and pelagic species. The model specification varies depending on the purpose of analysis. Leontief, translog, and quadratic functional forms are commonly used.

Applying a dual revenue function model of the generalized Leontief's form to the New England multispecies trawl fishery, Kirkley and Strand (1988) showed that the more commonly advocated forms of stock management, such as 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 (cod and yellowtail flounder) were estimated to be positive and significant, while those for incidental or bycatch species (pollock and other flounders) were not significant. The results revealed that restrictions on yellowtail flounder would increase the exploitation of cod, pollock, and haddock.

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 management of the fishery as an aggregate stock would be inappropriate. Own-price elasticities were positive for all species (octopus, cuttlefish, and squid) except cephalopods. The authors further concluded that the dominance of substitute relationships in the fishery would preclude the use of 'key species' management.

The dual revenue function approach was also used by Thunberg, Bresnyan, and Adams (1995) in analyzing the technical and economic relationships in Florida's near-shore commercial fishery. They estimated the translog revenue function. Own-price elasticities were positive and mostly significant. Cross-price elasticities were also all positive and mostly significant, indicating the complementary relations in production. These findings are consistent with the non-selective nature of the gillnet fishery. The complementary relationship was estimated to be strongest for mullet, which was the dominant species. The authors concluded that effective management of the fishery is possible through measures designed to regulate the harvest of mullet.

Squires and Kirkley (1991) estimated cost functions derived from the generalized Leontief revenue function to examine the fishers' short-run response to output quotas in California's fishery. They concluded that aggregate fishery quotas may be inappropriate for managing sablefish, as this may result in excessive discard of regulated species. They suggested alternative regulatory mechanisms, including license limitation, individual transferable quotas (ITQs), and trip quotas. Similarly, Squires (1987b) estimated long-run profit functions obtained from the translog revenue function to determine the technical and economic structure in the New England fishery. Own-price elasticities were inelastic for some species (yellowtail and other flounders) and elastic for others (cod and haddock). All cross-price elasticities were positive, indicating complementarity in production.

Empirical Procedures

Empirical Model

It is assumed that fishers pursue long-run profit maximization in two stages. The first stage involves selecting optimal vessel size, gear, design, and equipment. The second stage involves revenue maximization over a time horizon in which vessel size and characteristics are fixed (Campbell and Nicholl 1994). The empirical model specified below attempts to describe the behavior of fishers in the second stage.

The revenue function for the analysis of multispecies fisheries can be empirically specified either in a generalized Leontief flexible functional form as in Kirkley and Strand (1988), Campbell and Nicholl (1994), or in a translog form as in Thunberg, Bresnyan, and Adams (1995). In this study, the non-homothetic generalized Leontief revenue function is used. The choice of the generalized Leontief form hinges on the fact that it: (*i*) allows estimation in terms of output levels rather than revenue shares as in the translog; (*ii*) is linear in parameters; (*iii*) can deal with the non-homothetic technology; (*iv*) is one of the most useful forms in testing hypotheses regarding the structure of input use and output (Lopez 1985), and (*v*) does not lead to extreme variations in estimated elasticities as observed with translog function (Dixon, Garcia, and Anderson 1987). Analyzing the data in the level form can be more useful for fishery managers, as it provides the type of information they are familiar with (Kirkley and Strand 1988; Diop and Kazmierczak 1996; Bose, Campbell, and McIlgorm 2000). 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 of the Leontief form is given as:

$$R(Z, P) = \sum_i \sum_j \beta_{ij} (P_i P_j)^{1/2} Z + \sum_i \beta_i P_i Z^2 + \sum_i \delta_i P_i X_i Z, \tag{4}$$

where i and j denote fish species, Ps are output prices, Z is composite effort, Xs are stock abundance indices for individual fish species, and βs and δs are parameters to be estimated. The species aggregation, prices, composite effort, and stock indices will be described subsequently. Note that a more general specification may also include various other factors (season, location, port, *etc.*) and their interaction terms with Ps and Z. The specification given in equation (4) imposes only a few restrictions on the underlying technology. It implies linear homogeneity in output prices, jointness-in-inputs for the controllable factors of production, and nonjointness-in-inputs for the uncontrollable resource stock. Thus, the Leontief form is fairly flexible to examine the underlying economic interactions in Hawaii's longline fishery.

A system of input-compensated, revenue-maximizing output supply equations $Q_i^*(P, Z)$ is obtained by Hotelling's Lemma; *i.e.*, differentiating the revenue function (equation 4) with respect to prices as:

$$\frac{\partial R(P, Z)}{\partial P_i} = Q_i = \sum_{j \neq i} \beta_{ij} (P_j / P_i)^{1/2} Z + \beta_{ii} Z + \beta_i Z^2 + \delta_i X_i Z. \tag{5}$$

The presence of output cross-price interaction terms in equation (5) allows the possibility of jointness-in-inputs. Overall, nonjointness-in-inputs can be examined by testing the restriction that $\beta_{ij} = 0 \quad i \neq j$. Nonjointness-in-inputs for the k^{th} species can be determined by testing the restriction that $\beta_{kj} = 0 \quad k \neq j$. Separability between inputs and outputs can be ascertained by testing the restriction that $\beta_i = 0$. Finally, the symmetry condition can be tested using the restriction that $\beta_{ij} = \beta_{ji}$ for $i \neq j$.

The fishers' ability to change species mix of harvest for a given level of fishing effort in response to price changes can be analyzed in terms of own-price and cross-price output supply elasticities. The estimated supply equations [equation (5)] form the basis for computing own-price supply elasticities for each species and cross-price elasticities among the pairs of species. Accordingly, own-price elasticity of the i^{th} fish species (η_{ii}) can be estimated as follows:

$$\eta_{ii} = \frac{\partial Q_i}{\partial P_i} \cdot \frac{P_i}{Q_i} = -\frac{1}{2Q_i}\left[\sum_{j\neq i} \beta_{ij}(P_j/P_i)^{1/2} Z\right] \tag{6}$$

Similarly, the cross-price elasticity of the i^{th} species with respect to the j^{th} species (η_{ij}) can be computed as:

$$\eta_{ij} = \frac{\partial Q_i}{\partial P_j} \cdot \frac{P_j}{Q_i} = \frac{1}{2Q_i}\beta_{ij}(P_j/P_i)^{1/2} Z. \tag{7}$$

Effort elasticity (*i.e.*, supply response to a change in the amount of composite effort) for the i^{th} species (η_{iz}) can be computed as follows:

$$\eta_{iz} = \frac{\partial Q_i}{\partial Z} \cdot \frac{Z}{Q_i} = \left[\sum_{j\neq i} \beta_{ij}(P_j/P_i)^{1/2} + \beta_{ii} + 2\beta_i Z + \delta_i X_i\right] \cdot \frac{Z}{Q_i}. \tag{8}$$

A supply response to a change in stock conditions can be examined by computing elasticity with respect to the stock variable for each species as:

$$\eta_{ix} = (\partial Q_i / \partial X_i) \cdot (X_i / Q_i). \tag{9}$$

The estimated revenue function [equation (4)] also forms the basis for deriving shadow cost equation of effort: $C^* = W^*Z$, where W^* is derived as follows:

$$W^* = \frac{\partial R(P,Z)}{\partial Z} = \sum_i \sum_j \beta_{ij}(P_iP_j)^{1/2} + 2Z \cdot \sum_i \beta_i P_i + \sum_i \delta_i P_i X_i. \tag{10}$$

The firm may also adjust its level of composite effort in response to changes in output prices. The shadow price of effort depends on output prices and the level of quasi-fixed input, Z. This response can be assessed by deriving elasticity of effort with respect to individual output prices as:

$$\eta_{zp_i} = \frac{\partial Z}{\partial P_i}\frac{P_i}{Z} \tag{11}$$

$$= \frac{\left[(\sum \beta_i P_i) \cdot \left\{-\beta_{ii} - 0.5P_i^{-1/2} \cdot \left[\sum_j \beta_{ij}(P_j/P_i)^{1/2}\right] - \delta_i X_i\right\} - \left\{2Z \cdot (\sum \beta_i P_i)\right\} \cdot \beta_i\right]}{2Z \cdot (\sum \beta_i P_i)^2} \cdot P_i.$$

The demand for effort in the equation (11) is derived by rearranging equation (10) as: $Z = Z(P, W^*)$, which, in turn, forms the basis to compute the elasticity of effort with respect to price of each product. The relation given in equation (3) is used to examine economies of scope in terms of cost complementarity or anti-complementarity between a pair of outputs. Following Baumol, Panzar, and Willig (1988), the relative degree of economies of scope, multiproduct economies of scale, product product-specific economies of scale, and shadow cost elasticity are also examined.[3]

Species Aggregation

Hawaii's pelagic fisheries harvest numerous targeted as well as incidental species. For example, longline catch includes more than 20 different species. Therefore, for revenue function analyses, these species were aggregated to a smaller, manageable number of species or species groups. This was done based on catch and revenue shares, prices, and biological characteristics of fish species. Accordingly, longline species were aggregated to six species or species groups. These included yellowfin tuna, albacore tuna, bigeye tuna, broadbill swordfish, marlin, and other pelagic species. Marlin was an aggregate of black marlin, blue marlin, and striped marlin. Similarly, the other pelagic group included aku, barracuda, bluefin tuna, mahimahi, monchong, ono, opah, papio, sailfish, short nose, walu, and other unclassified pelagic species.

Bigeye tuna and swordfish are the two major species targeted by the longline fishers. Other species, such as yellowfin tuna, albacore tuna, marlins, and various other pelagic species are also commercially important. In swordfish trips, swordfish was the dominant species, accounting for 76% of total catch and 81% of total revenue during 1991–98. In mixed trips, swordfish was dominant, followed by bigeye tuna and yellowfin tuna, contributing to 48%, 21%, and 12% of total catch and 56%, 27%, and 13% of total revenue, respectively. In tuna trips, bigeye tuna was dominant, representing about 38% of total catch and 59% of total revenue. Yellowfin tuna, other pelagics, and albacore tuna contributed 10%, 16%, and 20% of total catch and 12%, 9%, and 8% of total revenue, respectively.

Comparing over time, the total catch of swordfish for the longline fishery has declined, while that of bigeye tuna increased due to effort reallocation from swordfish trips to tuna trips. For example, the contribution of swordfish to total longline revenue decreased from 52% in 1991 to 23% in 1998, while that of bigeye tuna increased from 28% to 49%. However, the catch composition has remained more or less the same for a given trip type over the study period.

The number of species categories included in the analysis is quite limited relative to the number of species landed. Only observations with complete information on outputs and prices of all species considered in the model could be used for estimation.[4] Observations with incomplete information were excluded. Hence, the larger

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[3] Mathematical details involved in calculating various aspects of multiproduct cost structure can be found in Squires and Kirkley (1991) and, hence, are not presented here.

[4] There were 6,666 trip records matched from different data sources; *i.e.*, the National Marine Fisheries Services (NMFS) logbook records and the Hawaii Division of Aquatic Resources (HDAR). The analysis included only 19% of 6,666 matched observations. In view of the exclusion of such a large number of observations, one may suspect that the efficient vessels that could minimize bycatch by selectively targeting only a limited number (1 to 3) of intended species may have been left out of the analysis. The analysis, however, included 116 or 70% of total vessels operating during 1991–98. Furthermore, the number of trips that composed three or fewer species was only about 8% of the 6,666 matched trips. The remainder of the trips had four or more species. Thus, the data demonstrates that the longline fishery is multispecies in nature as opposed to harvesting only one or two select species. In terms of proportions of vessels covered and similarities between the matched dataset and its subset that contains only complete information on prices and catches of all the species under consideration for the analysis, we feel that the dataset with the complete information used in the analysis is fairly representative of Hawaii's longline fleet.

the number of species used in the model, the larger would be the number of observations unavailable for estimation. At the same time, aggregation would also result in loss of information on individual species. Therefore, one has to keep this tradeoff in mind in selecting the number of species in the analysis and interpreting the results. As in Kirkley and Strand (1988), all estimates and derivations thereof are based on the observations with complete information about prices and catch of all species considered for the analysis.

Output Prices (P_i)

Output prices were computed implicitly using quantities sold and revenue received for each species.[5] In this study, we assumed that the fisher's decision to harvest a given quantity of a particular fish species is influenced by its expected price rather than the current price. Accordingly, current trip-level outputs were expressed as functions of prices obtained in the immediate preceding trip specific to the fisher.[6]

Effort Variable (Z)

Various vessel-specific (length, horsepower, gross registered tonnage, and net tonnage) and trip-level inputs (trip length, number of hooks, and number of sets) were considered in deriving a measure of composite input/effort. Based on the correlation coefficients of these variables, trip length and vessel net tonnage were selected in order to compute the composite effort.[7] A single composite effort or input (Z) was derived as the product of trip length (in days) and vessel net tonnage. This approach is similar to that used by Diop and Kazmierczak (1996) and Kirkley and Strand (1988), where the composite effort was computed as the product of trip length and vessel power. Campbell and Nicholl (1994) used the product of gross tonnage and the number of sets as composite effort.

Stock Variable (X)

Catch per unit of effort (CPUE) by species is the only available information on stock abundance of each species under consideration in our study. The measure is used as a proxy to assess the stock level of fish population (Campbell and Nicholl 1994). Clark (1976) also succinctly points out that the ratio of catch divided by effort is almost always taken as at least a rough indication of the current stock level of the fish population. Therefore, three CPUE measures were considered in the present study as a basis for creating stock indices variables. These included the number of fish landed per 1,000 hooks, total pounds landed per 1,000 hooks, and total pounds landed per fishing day for each

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[5] Prices of marlins and other pelagic species were computed as weighted averages of three marlin species and all other pelagic species, with weights being the shares of individual species in total catch of marlins and other pelagic species, respectively.

[6] This operation resulted in further loss of sizable number of observations; *i.e.*, 971 out of 2,242 observations could not be used simply because of lack of price information in preceding trips.

[7] The correlation coefficients among vessel power, vessel length, and vessel tonnage (both net and gross) ranged from 0.77 to 0.83. The correlation between vessel net tonnage and trip length was 0.40; 0.53 between the number of hooks and trip length; and 0.88 between the number of sets and trip length. This led us to choose vessel net tonnage and trip length as measures of composite effort.

species or species group.[8] These measures were found to be highly correlated. The number of fish per 1,000 hooks by species was used as a basis for the measure of stock abundance, as this measure is also adopted in other WPRFMC publications.

The stock variable (X) was expressed in terms of an index. This study used the species-specific stock index as a measure of stock abundance.[9] Species-specific stock indices were constructed for each quarter from individual fisher's trip level CPUE for each species. The entire set of trip observations in the matched dataset was used for this purpose. Then, trip-level CPUE was averaged quarterly over all fishers and trip types for each species or group of species considered in this study. The estimated species-specific quarterly CPUE was indexed by taking the CPUE measure for the first quarter of 1992 as a reference point. Thus, the index is one for the first quarter of 1992. The value greater (smaller) than one for any given quarter of a year implies a better (worse) stock situation for that quarter relative to the first quarter of 1992. The quarterly stock indices were created in a way that all fishers, regardless of the type of trip they choose, face the same stock or population level for a given quarter of a year for the given species. Instead of seasonal or annual dummies, quarterly stock indices for individual species were mainly used because they allow for the examination of supply responses to changes in stock situations for each species. They capture seasonal and annual stock variation, as well as the migratory pattern, recruitment, and other environmental aspects affecting CPUE.

Estimation

In view of differences in harvesting technologies and output composition among different trip types, revenue function analyses for the longline fishery were carried out separately for swordfish, mixed, and tuna trips.[10] This will provide information on how different trip types respond to changes in prices, fishing effort, and resource level. The data were examined for heteroskedasticity by applying the White test to each output supply function in equation (5) and also by plotting the residuals against the composite input by trip type. No significant heteroskedasticity was found at the 0.05 level. The systems of output supply functions were then estimated using Zellner's seemingly unrelated regression estimation (SURE) technique.[11]

Data

The U.S. National Marine Fisheries Service (NMFS) Honolulu Laboratory longline logbook and the State of Hawaii's Division of Aquatic Resources (HDAR) commercial catch records are the key sources of data involved in the study. The NMFS

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[8] Dupont (1990) used total catch weighted by trip length to create an index of stock abundance. We instead used the number of fish per 1,000 hooks to create a species-specific abundance index. Further, the number of fish rather than weight is believed to be a better proxy of fish population.

[9] However, monthly total catch (of all species under consideration) per unit of effort was used as a measure of stock abundance in Campbell and Nicholl (1994).

[10] Other studies have carried out separate analyses by vessel size; *e.g.*, in Kirkley and Strand (1988).

[11] The estimated system, in general, can be specified as $g = K\beta + \varepsilon$, where g is a (Nx1) vector of observations on catch, K is a (NxM) matrix of jointly exogenous variables in the system, β is a (Mx1) vector of unknown parameters to be estimated, and e is a (Nx1) vector of disturbances. When it is believed that error terms are contemporaneously correlated across equations, the SURE method is recommended. This method uses the estimates of the covariance of residuals across equations in an attempt to improve the efficiency of parameter estimates. The residuals obtained using the joint-generalized least squares procedure are used to estimate the error covariance matrix, which, in turn, is used to obtain the final SURE estimates.

logbook data provide information on fishing effort (such as trip length, number of sets, number of hooks, number of light sticks, *etc.*), trip type, fishing location, and number of fish caught by species. The HDAR data provide information on total pounds of fish caught and sold, number of fish caught, and revenue by species. Besides these data, additional vessel-specific information (such as tonnage, horsepower, size, *etc.*) was obtained from the data maintained by the U.S. Coast Guard.

The HDAR data are maintained at the trip level, while NMFS logbook data are at the set level. Therefore, the initial task involved the transformation of the logbook data from set level to trip level. Then, the data from the two sources were merged using some key identifying variables, such as vessel permit number/name, hauling and reporting dates, species, and the number of fish reported. For the period from 1991 to 1998, the trip-level longline observations in the NMFS logbook and HDAR datasets totaled 10,597 and 8,618, respectively, of which 6,666 were matched. The matched dataset represented about 77% of the total catch.[12] The dataset used in the estimation represented 70% or 116 of the 167 total vessels operating during the study period.[13] The data after the ban on swordfish harvest are not included because of data unavailability at the time of this analysis.

Results and Discussion

Summary statistics of the variables involved in estimating the dual revenue function models are presented in table 1 and those for all matched observations are presented in table 2. Comparing the two tables, the dataset used in the analysis (*i.e.*, those with complete information) and the matched dataset appeared to be fairly similar in terms of means and standard deviations of prices of individual species, catch levels, and effort variables. Comparing the values of the variables across trips, swordfish and bigeye tuna were caught in large amounts in the swordfish and tuna trips, respectively. In mixed trips, the amount of swordfish caught is higher than bigeye tuna. Bycatch (other pelagic species) was higher in the tuna trips compared to other trips. Mean prices of individual species are more or less similar across trips, but prices varied less for the primary target species in both the swordfish and tuna trips. Relatively larger vessels appeared to be taking more swordfish trips and mixed trips than tuna trips, and trip length was longer with swordfish trips than other trips.

Tests of Regularity Conditions

A dual-based revenue function should satisfy the following regularity conditions: (*i*) symmetry, (*ii*) monotonicity, (*iii*) convexity, (*iv*) concavity, and (*v*) homogeneity. All were examined in this study. The Likelihood Ratio (LR) tests of the symmetry condition suggested that the restricted estimates are the same as the unrestricted

[12] The mean statistics between the matched and unmatched data were similar. For example, on a per-trip basis the average number of hooks used, number of sets used, average number of fish caught, revenue, and total catch landed were (11,168 vs. 10,689), (9.82 vs. 9.11), (217 vs. 199), ($37,624 vs. $32,478), and (14,666 lbs. vs. 13,256) for the matched vs. unmatched datasets, respectively.

[13] A further comparison of the matched dataset with its subset data used in the analysis is given in tables 1 and 2. On average, quantities, proportions and prices by species, and fishing effort were fairly similar for each trip type.

Table 1
Mean Statistics of the Variables used in Estimating Longline Trip-level Output Supply Functions, 1991–98

	Swordfish Trips (n = 240)		Mixed Trips (n = 669)		Tuna Trips (n = 362)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Outputs (lbs./trip)						
Yellowfin tuna	1,195	1,268	1,704	2,200	1,632	1,923
Albacore tuna	822	1,229	566	808	2,919	3,992
Bigeye tuna	1,874	1,751	2,879	2,870	4,502	3,865
Swordfish	15,781	8,434	7,123	8,200	826	2,573
Marlin	1,089	1,319	1,351	1,574	2,025	1,588
Other pelagics	637	838	663	908	2,234	1,634
Expected prices (US$/lb.)						
Yellowfin tuna	2.97	1.17	3.10	1.22	2.88	1.06
Albacore tuna	0.98	0.60	1.26	0.62	1.41	0.56
Bigeye tuna	3.94	2.04	3.91	2.12	3.41	1.28
Swordfish	3.12	0.91	2.97	1.05	2.79	1.32
Marlin	1.47	0.77	1.41	0.75	1.28	0.56
Other pelagics	2.37	3.40	1.83	1.89	1.50	1.11
Effort						
Net tonnage	72.82	30.05	67.13	24.19	61.41	24.21
Trip length (days)	17.82	7.51	11.51	5.05	12.18	3.72
Stock index (1st Quarter of 1992 =1)						
Yellowfin tuna	1.47	0.73	1.56	0.80	1.59	0.81
Albacore tuna	1.69	1.36	1.73	1.13	2.19	1.28
Bigeye tuna	0.96	0.37	1.00	0.38	1.06	0.45
Swordfish	0.83	0.28	0.74	0.29	0.57	0.27
Marlin	0.96	0.22	0.98	0.23	0.95	0.29
Other pelagics	2.34	1.37	2.46	1.53	2.43	1.39

Note: n denotes the number of observations with complete information involving current trip-level outputs and lagged trip-level prices used in the analysis.

estimates in all trip types.[14] The homogeniety condition was not tested as the generalized Leontief function implies linear homogeneity. The models satisfied monotonicity globally. The supply equations also satisfied the concavity condition, except for the albacore supply equation in mixed trips and the marlin equation in tuna trips. Convexity was tested and the substitution matrix was found to be positive semi-definite for all trip types.[15] Thus, the revenue function and its supply correspondences satisfied the regularity conditions.

[14] The LR test values for swordfish trips, mixed trips, and tuna trips were 0.044, 0.0089, and 0.075, respectively. The $\chi^2(15)$ value of 24.99 at the 0.05 level suggests that the restricted estimates are the same as unrestricted estimates.
[15] The supply substitution matrices were found to be symmetric, and the determinants of these matrices for swordfish trips, mixed trips, and tuna trips were computed to be 0.0000563, 0.0000017, and 0.0000367, respectively.

Table 2
Mean Statistics of the Variables from all Matched Observations, 1991–98

	Swordfish Trips (n = 1,225)		Mixed Trips (n = 2,205)		Tuna Trips (n = 3,236)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Outputs (lbs./trip)						
Yellowfin tuna	986	1,152	1,570	2,042	1,460	1,888
Albacore tuna	948	1,733	620	1,136	2,816	4,020
Bigeye tuna	1,917	1,955	2,810	2,856	5,515	4,470
Swordfish	16,429	11,564	6,422	7,831	703	2,732
Marlin	738	1,096	1,202	1,416	1,712	1,499
Other pelagics	571	905	849	1,255	2,319	1,843
Expected prices (US$/lb.)						
Yellowfin tuna	2.99	1.30	3.10	1.37	2.87	1.12
Albacore tuna	1.07	0.71	1.27	0.61	1.48	0.61
Bigeye tuna	4.16	2.51	3.93	2.25	3.43	1.29
Swordfish	3.15	0.92	2.96	0.98	2.66	1.40
Marlin	1.51	0.92	1.32	0.75	1.34	0.60
Other pelagics	1.98	3.13	1.71	2.18	1.33	0.76
Effort						
Net tonnage	76.58	29.98	65.48	24.27	52.07	25.16
Trip length (days)	17.52	8.41	10.55	6.07	11.19	4.14
Stock index (1st Quarter of 1992 =1)						
Yellowfin tuna	1.47	0.65	1.54	0.78	1.54	0.76
Albacore tuna	1.33	1.08	1.50	1.16	1.97	1.30
Bigeye tuna	0.93	0.41	0.99	0.39	1.15	0.45
Swordfish	0.85	0.27	0.77	0.28	0.62	0.28
Marlin	1.04	0.31	1.07	0.32	0.96	0.33
Other pelagics	2.37	1.54	2.36	1.42	2.40	1.54

Note: n denotes the total number of observations in the matched dataset during 1991–98.

Parameter Estimates

The parameter estimates from the systems of supply equations are presented in table 3. The system weighted R^2 values were 0.110, 0.152, and 0.151 for swordfish, mixed, and tuna trips, respectively.[16]

Own-price coefficients are not directly estimated because output supplies are a function of prices normalized by own-prices. Most of the supply equations had a number of statistically significant coefficients. Altogether, about 40% of the coefficients were statistically significant. The coefficients associated with prices are best

[16] The R^2 values for individual OLS equations for each species are given in parentheses below. Swordfish trips: yellowfin (0.07), albacore (0.16), bigeye tuna (0.14), swordfish (0.21), marlin (0.06), and other pelagics (0.13) Mixed trips: yellowfin (0.15), albacore (0.05), bigeye tuna (0.10), swordfish (0.30), marlin (0.10), and other pelagics (0.25) Tuna trips: yellowfin (0.15), albacore (0.20), bigeye tuna (0.29), swordfish (0.18), marlin (0.16), and other pelagics (0.17).

Table 3
Parameter Estimates for Longline Trip-level Output Supply Functions

	Yellowfin	Albacore	Bigeye	Swordfish	Marlin	Others	Effort	Effort²	Stock
Swordfish Trips									
Yellowfin tuna		0.1146	–0.2073	–0.2073	0.3017**	0.1147*	–0.5283	0.0001	0.1866***
		(0.1007)	(0.1442)	(0.1343)	(0.1333)	(0.0619)	(0.3596)	(0.0001)	(0.0724)
Albacore tuna			–0.0617	0.1603*	–0.0009	0.1015**	–0.1941	–0.0001	0.2083***
			(0.0901)	(0.0899)	(0.1208)	(0.0469)	(0.3515)	(0.0001)	(0.0478)
Bigeye tuna				–0.0447	–0.2323*	–0.1189*	1.0927**	–0.0003***	0.6589***
				(0.1908)	(0.1303)	(0.0658)	(0.4797)	(0.0001)	(0.1531)
Swordfish		SYMMETRIC			0.0082	–0.0310	0.6738	–0.0001	3.1280***
					(0.1201)	(0.0671)	(2.3860)	(0.0005)	(1.0877)
Marlin						–0.0203	–0.2464	0.0001	0.1677
						(0.0632)	(0.4617)	(0.0001)	(0.2367)
Others							–0.0609	–0.0001	0.1084***
							(0.2061)	(0.0001)	(0.0197)
Mixed Trips									
Yellowfin tuna		0.1382*	–0.1410	–0.2546	0.1579	0.0027	–0.7196	–0.0002**	1.0245***
		(0.0704)	(0.2181)	0.2860)	(0.1581)	(0.0720)	(0.5145)	(0.0001)	(0.1073)
Albacore tuna			0.1260***	–0.2303***	–0.0994	0.0192	0.0759	0.0000	0.0706***
			(0.0475)	(0.0665)	(0.0922)	(0.0516)	(0.1831)	(0.0001)	(0.0282)
Bigeye tuna				0.2445	–0.4663***	–0.0502	1.0998	–0.0006***	1.3425***
				(0.3353)	(0.1147)	(0.0450)	(0.6818)	(0.0002)	(0.2883)
Swordfish		SYMMETRIC			0.7630***	0.0287	–0.3194	–0.0010***	11.0568***
					(0.1571)	(0.0756)	(1.4289)	(0.0004)	(0.9645)
Marlin						–0.0013	0.3691	–0.0002**	0.2097
						(0.0777)	(0.3706)	(0.0001)	(0.2344)
Others							–0.1026	–0.0001	0.2539***
							(0.1660)	(0.0001)	(0.0199)
Tuna Trips									
Yellowfin tuna		–0.3977	–0.6355	0.2968	0.1546	0.5153**	–0.4941	–0.0001	0.9204***
		(0.4799)	(0.4085)	(0.2940)	(0.2590)	(0.2291)	(0.9101)	(0.0004)	(0.1376)
Albacore tuna			–0.3347	0.2666	0.1854	0.1327	0.1582	–0.0011	1.2892***
			(0.5645)	(0.4053)	(0.3404)	(0.3101)	(1.7721)	(0.0008)	(0.1596)
Bigeye tuna				–0.6670*	–0.2183	–0.4450*	1.0652	–0.0014**	4.3535***
				(0.3466)	(0.2562)	(0.2688)	(1.5644)	(0.0007)	(0.4222)
Swordfish		SYMMETRIC			0.0044	0.3896	2.0581*	–0.0010**	1.5730***
					(0.1863)	(0.1843)	(1.0649)	(0.0005)	(0.5773)
Marlin						–0.0541	–1.4741**	0.0003	1.9335***
						(0.1984)	(0.7206)	(0.0003)	(0.3028)
Others							–0.0731	–0.0003	0.3278***
							(0.6913)	(0.0003)	(0.0692)

Figures in parentheses are standard errors. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.10 levels, respectively.

explained in terms of cross- and own-price elasticities.[17] Of particular interest in the estimated supply equations were the effort, squared-effort, and stock coefficients. The majority of the effort coefficients were positive, and the negative effort coefficients were mostly insignificant at the 0.05 level, except for marlin in tuna trips. The coefficients for the squared effort terms were mostly negative (in 77% of cases) and several of them were statistically significant, indicating that effort is characterized by diminishing marginal productivity. Because of interaction of effort with stock indices, the effect of effort on output supplies is better explained in terms of effort elasticities rather than their coefficients in supply equations. The stock coefficients were all positive and mostly significant at the 0.01 level, indicating a positive effect of stock level on output supplies of all species categories.

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[17] The parameter estimates from a Leontief function do not have much economic meaning on their own. They simply are useful in determining elasticity values.

Tests of Hypotheses

The results of tests of hypotheses for nonjointness-in-inputs and input-output separability are presented in table 4. The hypothesis of nonjointness-in-inputs is rejected for all outputs taken together as well as for most individual species for all trip types. The rejection of the nonjointness-in-inputs hypothesis suggests that there are significant technical interactions among species landed by longliners, implying that single species regulation would affect the exploitation of unregulated species. The recent ban on swordfishing in certain Hawaiian waters geared toward managing sea turtles and other endangered species rather than managing swordfish *per se* may, however, affect the exploitation of the other species since the longline fishery is characterized by a joint production process.

Table 4
Tests of Hypotheses of Nonjointness-in-Inputs and Input-Output Separability

	F-Value			
	F-Value	Degrees of Freedom	Pr>F	Decision ($\alpha = 0.05$)
Swordfish Trips				
Nonjointness-in-inputs ($\beta_{ij} = 0 \quad i \neq j$)				
Overall	2.13	15;1401	0.00	Reject null
Yellowfin tuna	2.24	5;1401	0.04	Reject null
Albacore tuna	3.45	5;1401	0.00	Reject null
Bigeye tuna	1.70	5;1401	0.13	Accept null
Swordfish	1.26	5;1401	0.27	Accept null
Marlin	1.37	5;1401	0.23	Accept null
Other pelagics	1.94	5;1401	0.08	Reject null
Input-output separability ($\beta_i = 0$)	1.45	6;1401	0.19	Accept null
Mixed Trips				
Nonjointness in inputs ($\beta_{ij} = 0 \quad i \neq j$)				
Overall	3.85	15;3975	0.00	Reject null
Yellowfin tuna	1.18	5;3975	0.31	Accept null
Albacore tuna	4.52	5;3975	0.00	Reject null
Bigeye tuna	4.18	5;3975	0.00	Reject null
Swordfish	7.53	5;3975	0.00	Reject null
Marlin	7.83	5;3975	0.00	Reject null
Other pelagics	0.39	5;3975	0.85	Accept null
Input-output separability ($\beta_i = 0$)	1.24	6;3975	0.28	Accept null
Tuna Trips				
Nonjointness in inputs ($\beta_{ij} = 0 \quad i \neq j$)				
Overall	1.63	15;2133	0.05	Reject null
Yellowfin tuna	2.16	5;2133	0.05	Reject null
Albacore tuna	0.32	5;2133	0.90	Accept null
Bigeye tuna	2.27	5;2133	0.04	Reject null
Swordfish	1.57	5;2133	0.16	Accept null
Marlin	0.22	5;2133	0.95	Accept null
Other pelagics	2.63	5;2133	0.02	Reject null
Input-output separability ($\beta_i = 0$)	1.37	6;2133	0.22	Accept null

The results showed insufficient evidence for rejecting the null hypothesis of separability between inputs and outputs for all trip types at the 0.05 level, suggesting that the management of the longline fishery as one single fishery may be appropriate. In fact, this result is consistent with past management of the fishery through area or seasonal closure or by using the “limited entry” permit system where the objective was to manage the entire fishery rather than managing individual species.

Elasticities

The estimated own-price, cross-price, effort, and stock elasticities of output supplies, along with their standard errors by trip type are given in tables 5 through 7. Elasticities and standard errors were calculated at the sample mean values. Although theory suggests that own-price supply elasticities be positive, some of the own-price elasticities were negative but statistically insignificant, except for albacore in swordfish trips. Although insignificant at the 0.05 level, own-price elasticities for major targeted species like swordfish in swordfish trips or bigeye tuna in tuna trips were positive. All own-price elasticities were inelastic.[18] The results are comparable with many earlier studies where own-price elasticities are mostly inelastic and not all are consistently positive and significant. Moreover, own-price elasticities for some species are negative and statistically significant as in Squires (1987b) and Bose, Campbell, and McIlgorm (2000). It shows fishers’ limited ability to control the species mix given the stock uncertainty of pelagic species due to their highly migratory nature.

The estimates of cross-price output supply elasticities revealed both the substitution and complementary production relationships among species landed by the Hawaii’s longline fishery. The cross-price supply elasticities were all inelastic. As shown in tables 5 through 7, only about 33% of the cross-price elasticities were statistically significant and the rest were insignificant, suggesting that fishers have limited ability to adjust the species mix and amount of output in the short run in response to exogenous price changes. Instead, product mix largely depends on resource abundance (Segerson and Squires 1993).

In swordfish trips, a significant complementary relationship existed between yellowfin and marlin, yellowfin and other pelagics, albacore and swordfish, and albacore and other pelagics (table 5). A significant substitute relationship existed between bigeye tuna *vs.* marlin, and bigeye tuna *vs.* other pelagics. The decline in outputs of marlin and other pelagics due to an increase in bigeye tuna price was much larger than the decline in output of bigeye tuna due to a price increase of marlin and other pelagic species.

In mixed trips, a number of statistically significant complementary relationships existed between yellowfin tuna and albacore, bigeye tuna and albacore, and swordfish and marlin (table 6). Statistically significant substitute relationships were observed between bigeye tuna *vs.* marlin and swordfish *vs*. albacore. The decline in output of marlin due to an increase in the price of bigeye tuna would be much larger than the decline in bigeye tuna output due to an increase in the price of marlin. Similarly, the effect of a change in swordfish price on albacore output would be much larger than the effect of albacore price on swordfish output.

In tuna trips, the “others” category showed a significant complementary rela-

[18] These trip-level elasticities are smaller in absolute values than those over a longer period due to Le Chatelier’s principle (Squires and Kirkley 1991).

Table 5
Price, Effort, and Stock Elasticities of Trip-level Output Supply Functions — Swordfish Trips

Quantity Supplied	Price Change						Effort Elasticity	Stock Elasticity
	Yellowfin	Albacore	Bigeye	Swordfish	Marlin	Others		
Yellowfin tuna	0.0410 (0.4153)	0.0383 (0.0336)	–0.1386 (0.0964)	–0.1234 (0.0799)	0.1232*** (0.0544)	0.0595** (0.0321)	–0.1467 (0.1778)	0.3180*** (0.1234)
Albacore tuna	0.1677 (0.1474)	–0.4364** (0.2184)	–0.1041 (0.1520)	0.2408** (0.1351)	–0.0009 (0.1245)	0.1328** (0.0614)	0.4860** (0.2173)	0.5942*** (0.1363)
Bigeye tuna	–0.0665 (0.0462)	–0.0114 (0.0166)	0.1791 (0.4662)	–0.0147 (0.0628)	–0.0524* (0.0294)	–0.0341* (0.0189)	0.3641*** (0.1479)	0.4676*** (0.1087)
Swordfish	–0.0089 (0.0057)	0.0039* (0.0022)	–0.0022 (0.0094)	0.0081 (0.4866)	0.0002 (0.0036)	–0.0012 (0.0026)	0.2411*** (0.0389)	0.2296*** (0.0798)
Marlin	0.2725** (0.1204)	–0.0004 (0.0628)	–0.2420* (0.1358)	0.0076 (0.1114)	–0.0214 (0.3880)	–0.0164 (0.0511)	0.1201 (0.1501)	0.2067 (0.2918)
Others	0.1394** (0.0752)	0.0710** (0.0328)	–0.1665* (0.0922)	–0.0387 (0.0836)	–0.0173 (0.0541)	0.0121 (0.1656)	0.1152 (0.1170)	0.5518*** (0.1005)

Figures in parentheses are standard errors. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.10 levels, respectively.

Table 6
Price, Effort, and Stock Elasticities of Trip–level Output Supply Functions — Mixed Trips

Quantity Supplied	Price Change						Effort Elasticity	Stock Elasticity
	Yellowfin	Albacore	Bigeye	Swordfish	Marlin	Others		
Yellowfin tuna	0.0501 (0.6904)	0.0209** (0.0107)	–0.0377 (0.0583)	–0.0593 (0.0666)	0.0254 (0.0254)	0.0005 (0.0132)	0.1500 (0.1273)	0.7598*** (0.0796)
Albacore tuna	0.1549** (0.0790)	–0.0021 (0.1907)	0.1588*** (0.0599)	–0.2528*** (0.0730)	–0.0753 (0.0699)	0.0166 (0.0445)	0.2434*** (0.0997)	0.1749*** (0.0698)
Bigeye tuna	–0.0177 (0.0273)	0.0101*** (0.0038)	0.0219 (0.7116)	0.0300 (0.0411)	–0.0395*** (0.0097)	–0.0048 (0.0043)	0.3939*** (0.0853)	0.3787*** (0.0813)
Swordfish	–0.0148 (0.0166)	–0.0085*** (0.0025)	0.0160 (0.0219)	–0.0239 (0.8629)	0.0300*** (0.0062)	0.0013 (0.0034)	0.7543*** (0.0631)	0.9336*** (0.0814)
Marlin	0.0701 (0.0701)	–0.0281 (0.0261)	–0.2325*** (0.0572)	0.3315*** (0.0683)	–0.1405 (0.4618)	–0.0004 (0.0265)	0.3931*** (0.1073)	0.1240 (0.1386)
Others	0.0022 (0.0572)	0.0097 (0.0261)	–0.0448 (0.0402)	0.0223 (0.0588)	–0.0007 (0.0417)	0.0113 (0.2086)	0.3548*** (0.0971)	0.7625*** (0.0597)

Figures in parentheses are standard errors. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.10 levels, respectively.

tionship with swordfish and yellowfin tuna (table 7). Bigeye tuna's cross-price elasticity with respect to swordfish was both negative and significant, indicating substitution in production. Moreover, swordfish cross-price elasticity with respect to bigeye tuna price was higher than the bigeye tuna cross-price elasticity with respect to the swordfish price, indicating that an increase in the price of bigeye tuna would reduce the output of swordfish more than the decrease of bigeye tuna output due to an increase in swordfish price.

These results demonstrate fishers' revenue maximization behavior by harvesting high-priced, highly abundant species like bigeye tuna, swordfish, and yellowfin against relatively low-priced species like albacore, marlin, and other pelagics. The existence of these substitute relationships suggests that single-species management of the longline fishery may have negative effects on unregulated species through unanticipated shifts in production. Lack of significant complementary relationships across all species, especially across the important, high-valued species like bigeye tuna, swordfish, and yellowfin, suggests some degree of selective harvesting on the part of fishers and incomplete joint production.

Also presented in tables 5 through 7 are the estimates of output elasticities with respect to the composite effort by trip type. The estimates of effort elasticities were positive for all species except yellowfin tuna in swordfish trips, and most of them were significant at the 0.05 level. Thus, the results suggest that output supplies respond positively to an increase in the level of composite effort. Effort elasticities were all inelastic, except for swordfish in tuna trips. A significant substitute relationship between bigeye tuna with swordfish in tuna trips raises the possibility of increased exploitation of bigeye tuna in light of recent swordfish harvest restriction. Some swordfish discards may be anticipated, but such discards may be limited, as the average number of swordfish caught per tuna trip during 1991–98 was only 2.69, which is well within the allowable catch limit; *i.e.*, a vessel can sell up to 10 swordfish/trip if caught during a tuna trip.

Estimates of stock elasticities for each species, indicating a supply response to their seasonal stock fluctuations, are shown in the last column of tables 5 through 7. Stock elasticities were all positive and mostly significant at the 0.01 level for most species for all trip types. Most of the stock elasticities were inelastic, implying that outputs responded by a lesser magnitude relative to the variation in their stock levels.

Finally, elasticities of composite effort with respect to individual output prices are presented in table 8. It was generally observed that an increase in fish prices resulted in a positive effect on fishing effort. Except for yellowfin tuna in swordfish trips, price elasticities of effort were all positive, suggesting that higher fish prices would increase the level of effort devoted to longline fishing. Effort was output price elastic for swordfish in swordfish and mixed trips. Effort was also modestly responsive for bigeye tuna in all trip choices. In other cases, output prices had little effect on effort devoted to the longline fishery.

Multiproduct Cost Structure

Economies of scope provide a measure of cost savings (or in the present context revenue increases) through product diversification when production is joint-in-inputs. The shadow cost complementarities (or anti-complementarities) are an important source of economies (or diseconomies) of scope. These measures were derived using a relationship between multiproduct cost and revenue functions given in equation (3). These results indicated the existence of cost complementarities in swordfish trips, implying that increased production of product i would lower the

Table 7
Price, Effort, and Stock Elasticities of Trip–level Output Supply Functions — Tuna Trips

Quantity Supplied	Price Change						Effort Elasticity	Stock Elasticity
	Yellowfin	Albacore	Bigeye	Swordfish	Marlin	Others		
Yellowfin tuna	0.0476	–0.0656	–0.1631	0.0690	0.0243	0.0879**	0.2984**	0.6909***
	(1.1332)	(0.0792)	(0.1049)	(0.0683)	(0.0407)	(0.0391)	(0.1587)	(0.1033)
Albacore tuna	–0.0750	0.0528	–0.0687	0.0496	0.0233	0.0181	0.2275	0.7474***
	(0.0905)	(1.5765)	(0.1159)	(0.0753)	(0.0428)	(0.0423)	(0.1605)	(0.0925)
Bigeye tuna	–0.0500	–0.0184	0.1567	–0.0517**	–0.0114	–0.0253*	0.2952***	0.7955***
	(0.0321)	(0.0310)	(1.2081)	(0.0268)	(0.0134)	(0.0153)	(0.1023)	(0.0772)
Swordfish	0.1404	0.0882	–0.3433**	–0.0199	0.0014	0.1332**	1.4362***	0.8459***
	(0.1391)	(0.1340)	(0.1784)	(0.9609)	(0.0587)	(0.0630)	(0.2643)	(0.3104)
Marlin	0.0441	0.0370	–0.0678	0.0012	–0.0034	–0.0112	0.3184***	0.6985***
	(0.0739)	(0.0679)	(0.0795)	(0.0524)	(0.8495)	(0.0409)	(0.1313)	(0.1094)
Others	0.1229**	0.0221	–0.1155**	0.0915**	–0.0086	–0.1125	0.2995***	0.2755***
	(0.0546)	(0.0517)	(0.0697)	(0.0433)	(0.0315)	(0.8175)	(0.1035)	(0.0581)

Figures in parentheses are standard errors. ***, **, and * denote statistical significance at the 0.01, 0.05, and 0.10 levels, respectively.

Table 8
Elasticities of Composite Effort with Respect to Output Prices

Species	Swordfish Trips	Mixed Trips	Tuna Trips
Yellowfin tuna	–0.067	0.122	0.146
Albacore tuna	0.007	0.020	0.104
Bigeye tuna	0.728	0.548	0.623
Swordfish	2.225	1.813	0.295
Marlin	0.028	0.057	0.073
Others	0.029	0.052	0.057

marginal cost of product j, for $i \neq j$. Cost anti-complementarities were dominant in mixed and tuna trips, where increased production of one species would increase the marginal cost of others. Thus, these results revealed some interesting patterns. For example, in swordfish trips where the primary target includes a single species (*i.e.*, swordfish), cost complementarities were dominant. On the other hand, in the case of multiple species targeting, as in mixed and tuna trips, cost anti-complementarities were dominant. Shadow unit prices of composite effort (*i.e.*, product of trip length in days and vessel net tonnage), in terms of marginal revenue forgone, were \$10.66, \$15.63, and \$27.83 for swordfish, tuna, and mixed trips, respectively. Accordingly, per-trip total shadow costs were estimated to be \$14,776, \$12,044, and \$22,561, respectively. Multiproduct economies of scale (*i.e.*, the ratio between total shadow cost and total revenue) for swordfish, tuna, and mixed trips were computed to be 0.23, 0.37, and 0.54, respectively, indicating decreasing returns to scale for all trip types. Thus, firms do not realize cost or revenue advantages from harvesting more fish in fixed proportions when prices and resource abundance are constant.

Except for yellowfin in swordfish trips, incremental costs (*i.e.*, costs involved in including a given species in production) were positive in all cases, implying that including these species in longline harvest would increase costs. Total incremental costs were highest for primary targets, such as swordfish in swordfish and mixed trips and bigeye tuna in tuna trips. Similarly, average incremental costs were highest for swordfish in tuna and mixed trips, followed by bigeye tuna in swordfish and mixed trips.

The relative degree of shadow economies of scope indicated that in swordfish trips joint production of each species would result in some cost increases (or revenue losses in the revenue function context) rather than producing them individually. However, producing different species jointly or individually would have no notable effects on tuna and mixed trips, except for other species. The production of other species individually would result in cost increases in mixed trips but decreases in tuna trips. Except for albacore tuna in swordfish trips and swordfish in tuna trips, product-specific economies of scale were all less than unity, indicating decreasing returns to scale. Shadow cost elasticity was highest for primary targets, such as swordfish in swordfish trips and bigeye tuna in tuna trips.

Conclusion

The main purpose of this study was to analyze technical and economic interrelationships among species harvested by Hawaii's longline fishery during 1991–98 by estimating the dual supply functions derived from the generalized Leontief revenue function. The results revealed some significant substitution and complementary relationships, which should be taken into account when some species are considered for regulation. The hypothesis of nonjointness-in-inputs was rejected for all trip types, indicating that Hawaii's longline fishery is characterized by a joint production process. Thus, any effort restriction on one species may result in a production decline of all species. From a fishery management perspective, the results indicated that the regulation of a single species may affect the exploitation of other species. In other words, traditional single-species regulation would be inappropriate in managing the longline fishery. The hypothesis of input-output separability was not rejected for all trip types. This suggests that the longline fishery can be managed as a whole rather than focusing on individual species. This finding is consistent with Hawaii's past fishery management through area or partial seasonal closure and by the 'limited entry' permit system, where the primary focus has been the entire fishery rather than individual species.

Although own-price elasticities were statistically insignificant, the longline fishers appeared to be behaving rationally in their output supply decisions for all types of trips, as evidenced by the symmetric and positive semidefiniteness of the supply substitution matrices.[19] Given stock uncertainty and the fishers' limited ability to control species-mix, fishers seemed to be more inclined to maximize total catch and revenue rather than being very selective on desired species. However, substantial economic and technical interactions were found to exist as evidenced by a number of significant cross-price elasticities, indicating either complementary or substitution relations in production among pairs of species. However, such interactions varied by trip choices and fish species. The estimated cross-price elasticities provide evidence of the need for fishery managers to account for underlying technical and economic interactions inherent in the longline fishery when a species regulation is under consideration. The existence of substitute relationships in the longline fishery also suggests that single-species management of the longline fishery may have negative effects on unregulated species through unanticipated shifts in production, therefore requiring the management of more than one species. The recent regulation aimed at banning the harvest of swordfish by Hawaii's longliners is an example of single-species regulation. Because of jointness-in-production, regulating swordfish catch would affect the harvest of other species in tuna trips.

Based on the nature of substitute relationships among some species, there was a general tendency that declines in outputs of a relatively lower-valued species due to an increase in prices of high-valued species were greater than the declines in the outputs of a higher-valued species due to an increase in the prices of relatively low-valued species. It also demonstrates fishers' revenue maximization behavior by harvesting high-priced species like bigeye tuna, swordfish, and yellowfin tuna against relatively low-priced species like albacore tuna, marlin, and other pelagics whenever the higher-valued species are abundantly available. As expected, both effort and stock elasticities of output supplies were positive and significant, yet inelastic in most cases. Similarly, the composite effort elasticities with respect to individual species prices were also positive, yet inelastic for all trip choices.

Besides testing hypotheses of nonjointness-in-inputs and input-output separability and deriving the various output supply and effort elasticities, multiproduct shadow cost structure (multiproduct economies of scope and scale, product-specific economies of scope and scale, and cost elasticities) was also examined to improve

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[19] The symmetric and positive semidefiniteness of the output supply substitution matrix suggests that output supply increases with an increase in its own prices, and if the price of an input increases, the demand for the input decreases (Mas-Colell, Whinston, and Green 1995).

the understanding of technical and economic interrelationships in Hawaii's longline fishery. The results showed decreasing returns to scale. Cost complementarities were dominant in swordfish trips, while cost anti-complementarities were dominant in mixed and tuna trips. Product-specific economies of scale also revealed decreasing returns to scale for most species. Although the production was characterized to be joint-in-inputs, based on degree of shadow economies of scope, overall joint production did not reveal any cost advantages. Perhaps this may again be attributed to fishermen's limited ability to choose an optimal output-mix due to bycatch.

The technical and economic interrelationships inferred from this study may also be useful in ecosystem-based fishery management. The fishery managers will be able to assess how regulation of one species can affect other, unregulated species. This information will be particularly useful in assessing the impacts of the recent ban on targeting swordfish by longliners in an effort to minimize sea turtle interactions with shallow-set swordfish longlining. The regulation also applies to swordfish catches in tuna trips. A significant substitute relationship between bigeye tuna and swordfish in tuna trips suggests some possibility of increased exploitation of bigeye tuna when swordfish harvest is imposed. However, the exploitation of bigeye tuna *vis-à-vis* swordfish discard due to swordfish harvest restriction may not be serious, as a fisher is still allowed to market up to ten swordfish caught in a tuna trip. The average number of swordfish caught per tuna trip in the past (during 1991-98) was only 2.69, which is well within the allowed limit. However, the new regulation requires all longline vessels to redirect their harvesting strategies to species other than swordfish by setting hooks deeper. The consequent increase in tuna trips primarily due to a shift of some vessels previously taking swordfish and mixed trips may result in increased exploitation of bigeye tuna along with other species that were previously less exploited. Moreover, a large number of small-scale fisheries, like trollers and handliners, that largely rely on tunas and other pelagic species may be affected over time by extensive/intensive extraction of tunas and other pelagic species by larger commercial longline vessels, the impact of which has yet to be assessed. In the light of these concerns, it would be useful to extend this study to analyze data after the swordfish harvest ban. Such a comparative study before and after a regulation can be quite useful in evaluating the effects of existing regulations as well as in considering future regulations.

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