Modeling the Effects of Area Closure and Tax Policies: A Spatial Model of the Hawaii Longline Fishery

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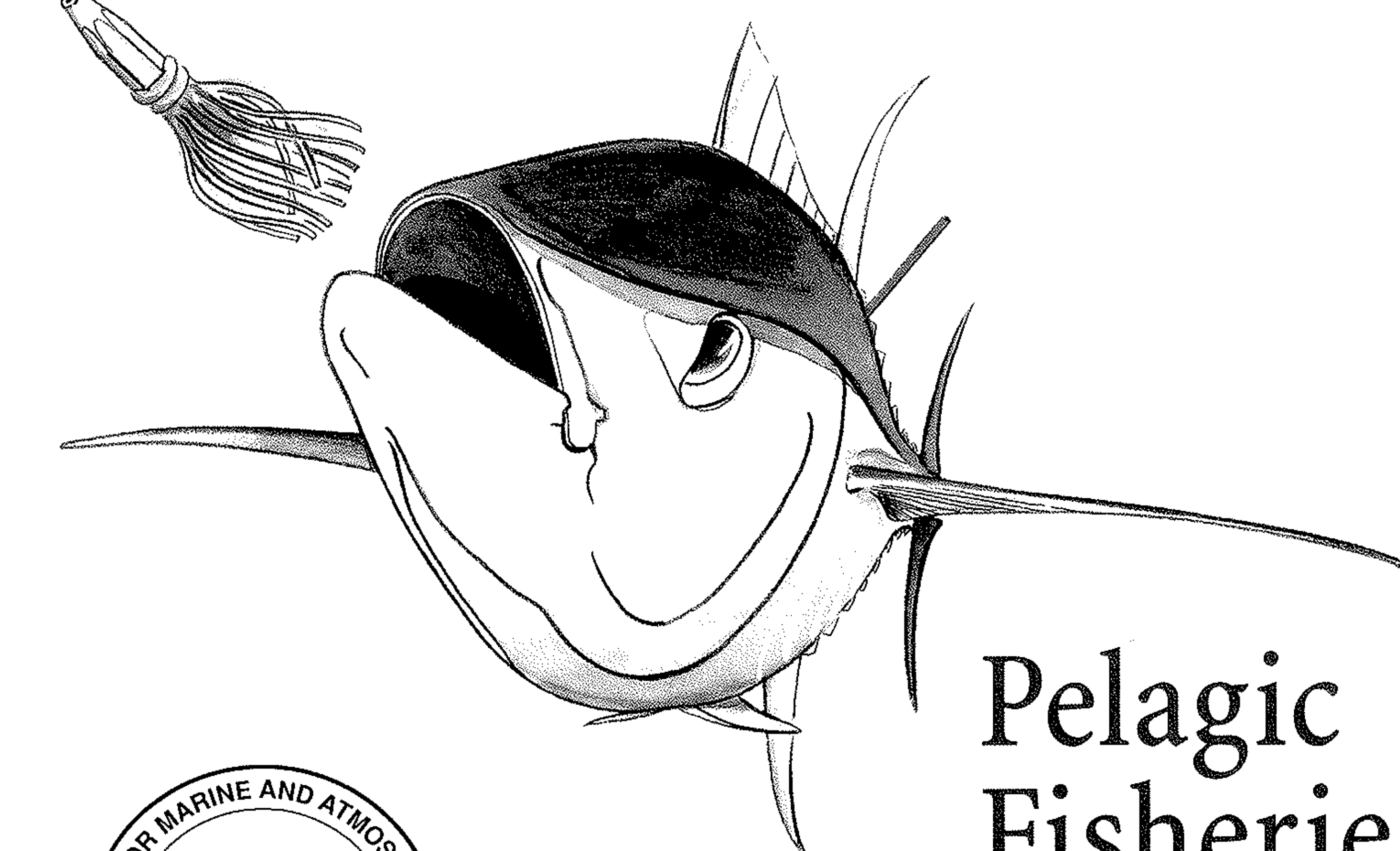

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Pelagic Fisheries Research Program

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ABSTRACT

We develop an economic model for a multi-species fishery that incorporates the spatial distribution of effort and fish stocks. Catchability coefficients and initial stocks are estimated from catch and effort data for each specific location. Vessels are allocated over space and time to locations of maximum profit which decline with harvest because of stock externalities. A supply function for labor allocation in the fishery is estimated. The simulated model is applied to the Hawaii longline fishery. The economic impacts of regulatory policies such as reduction of inshore gear conflict and conservation of offshore turtle populations is examined.

Key words: spatial-dynamic models, fisheries regulation, area closures, fishing effort, longline fisheries

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Contents

1. INTRODUCTION

Individual Transferable Quotas (ITQs) have been heralded by many fishery economists as the panacea for the management problems that beset most of the world's fish stocks. In a comprehensive review of the regulatory experience with ITQs, Squires, Kirkley, and Tisdell (1995) suggest that many countries have preferred input controls to ITQs in fisheries with multiple species and bycatch problems as well as in situations where the costs of monitoring, enforcement, and resource assessment are significant. Other "second best" management measures such as area closures and gear restrictions have been adopted in more complex fisheries in several countries such as the United Kingdom, Norway, and Italy. Area and seasonal closures have also been popular in the management of migratory species such as tuna in the Atlantic and Pacific Oceans (Gribble and Dredge, 1994).

There is a large body of literature (see survey by Townsend, 1990) that examines the economic and biological impacts of alternative regulatory policies such as ITQs and various forms of limited entry programs (e.g., gear restrictions). Most published studies have either focused on a single regulatory instrument such as a quota on harvest or gear restriction or a combination (Moussali and Hilborn, 1986; Stollery, 1984). Other analyses have attempted to endogenize the length and timing of closures in a programming model of stock recruitment (Watson, Die, and Restrepo, 1993). These models, by and large, implicitly assume away substitution effects of area closures, i.e., when a certain fishing ground is closed, effort may be reallocated elsewhere. Several studies suggest that these substitution effects may be quite significant. For example, Cadrin et al. (1995) point out that when stocks are migratory, closure of inshore areas to more efficient vessels "may not confer the expected benefits because fishing effort will be displaced to unprotected areas." Closure of inshore fishing areas led to increased allocation of effort to onshore fishing grounds in the Gulf of Mexico brown shrimp fishery (Gracia, 1997). Very recently, lawyers for the Earthjustice Legal Defense Fund concerned about turtle bycatches in the North Pacific successfully argued that substitution of boats to other regions will minimize the impact of a moratorium on fish harvests in the North Hawaiian Ocean. As a result, U.S. District Judge David Ezra took the "unprecedented" step of restricting Hawaii longliners from fishing north of 28 degrees latitude. (TenBruggencate, 1999).

In what follows, we examine the economic impacts of area closure and tax policies by developing a model that explicitly incorporates both the spatial and dynamic elements. The model has several unique features that include (i) estimation of the catch-abundance relationship for a multispecies fishery by spatial location, (ii) sequential allocation of vessels over a spatial grid using a crew-profit maximizing criterion, and (iii) estimation of a labor supply function based on the labor-leisure trade-off. The model is applied to the spatial and dynamic allocation of longline vessels in the Hawaii pelagic fishery. Model results are found to predict actual vessel allocation data reasonably accurately. The model is then used to generate economic impacts under alternative area closure restrictions and tax policies.

The differential impact of area closure policies that reduce inshore gear conflict and turtle bycatch in offshore fisheries is compared with an increase in the tax on harvest. It is found that harvest taxes have a minimal impact in achieving conservation objectives relative to area closures. Harvest taxes have little effect on industry revenue but reduce crew wages and boat owner in-

comes by about 20 percent. Area closure policies that reduce turtle by-catch in the northern latitudes also block access to lucrative swordfish fishing grounds, but they have a relatively small impact on vessel profits. This is because boats are able to switch to inshore fishing areas. Policies that reduce gear conflict in inshore areas have the smallest impact on crew income and result in reduced harvests of the major inshore species.

While the individual elements of the proposed model are not novel, we believe that the inclusion of a spatially non-uniform distribution of fish stocks and harvesting costs in obtaining the equilibrium allocation of vessels over time and space helps develop a modeling framework which is powerful in predictive capacity and policy analysis. The spatial feature allows for differential accounting of vessel travel costs from port and fishing costs by location. The dynamic nature of the model allows for stock externalities and exogenous changes in demand and cost parameters and in the longer term, discounting can be easily incorporated. In future work, biological information on the spatial migration of pelagic fish stocks can be included to determine instantaneous fish stocks net of harvest and migration. Extension to multiple ports of origin and political jurisdictions is straightforward.

The paper is organized as follows: Section 2 details the elements of the proposed model. Section 3 describes the calibration of 5 using data from the Hawaii pelagic fishery. Section 4 demonstrates model application by examining impacts of regulatory policy changes. Section 5 concludes the paper.

2. THE MODEL

The model is based on a standard framework of maximization of fleet profit in the short run, where the allocation of fishing effort is determined over space based on the comparison of net revenues from each fishing location. The fishery can be thought of as a regulated open access fishery, where seasonal closures are used to achieve regulatory objectives such as species and by-catch conservation. The net revenues in turn are dependent on stock sizes of each species and allocated fishing effort in fishing locations as well as exogenous fish price and catchability of each species. Price and various stock sizes across fishing regions in each period influence the fleet revenue per trip, while the distance between the harbor and each fishing area affect travel costs. As more trips are allocated into a particular fishing area, the expected revenue per trip from the area diminishes due to the stock externality. Boats are divided according to whether they target swordfish or tuna, as explained below, which in turn affects the catchability of different species. In equilibrium, the average net returns per trip are equalized across locations.

Catch Function

Consider a fishery in which there are I species of fish (e.g., swordfish, bigeye, and yellowfin) denoted by $i = 1,...,I$ and K fishing areas or locations, indexed by $k = 1,...,K$. Stocks of different species are assumed to be known at the beginning of a given time period in each area. These time periods are chosen to be sufficiently short such that in each area, stock changes within a period due to fish reproduction, natural mortality, and stock migration across areas can be ignored; i.e., fish stocks within a period are expected to decrease only due to harvesting.

Let the catch function over this unit time period be given by

$$C_{i,k} = \left(1 - e^{-f(E_k, \gamma_i)}\right) B_{i,k} \tag{1}$$

where $C_{i,k}$ is the catch of species i in area k, γ_i is a vector of the catchability coefficient for species i, E_k is a vector of fishing effort (e.g., number of hooks) in area k, and $B_{i,k}$ is the fish stock for species i in area k. In (1), the instantaneous fishing mortality rate, f, is defined as a linear sum of effort by set types,

$$f(E_k, \gamma_i) = \sum_s \gamma_{i,s} E_{k,s}, \tag{2}$$

where s represents alternative set types (e.g., tuna or swordfish set), $\gamma_{i,s}$ and $E_{k,s}$ are respectively, the catchability coefficient and the amount of fishing effort by set type s. Vessel trips need to be differentiated by whether they target swordfish or tuna (or both), since the cost structure and the catchability vary depending on the species targeted during the trip.

A slightly more generalized form of (1) has been used by Clark (1985) and Deacon (1989) although they do not consider heterogeneity in the targeting of species. The term $\left(1 - e^{-f(E_k, \gamma_i)}\right)$ is defined as the fishing mortality rate that depends on the level of labor, the particular species targeted, the type of boat and gear used. Its magnitude is always less than unity. Several restrictions are imposed on the above catch function. We assume that the fish stock is "infinitely diffusive" within area k; i.e., the density of fish is linearly related to the residual stock size and is distributed uniformly within each fishing area (Clark, 1985).

Revenue from a Fishing Trip

We assume that ex-vessel fish prices are given. Although not attempted here, a demand function for each species can be substituted at the cost of additional model complexity. Implicitly, we assume that each boat has perfect knowledge of the fish stock in area k. Then the total revenue from fishing in area k is obtained by summing over revenues from each species. The average revenue per trip in area k, $AR_{Trip,k}$, can then be expressed as

$$AR_{Trip,k} = \frac{\sum_i P_i C_{i,k}}{N_k} = \frac{\sum_i P_i \left(1 - e^{-f(E_k, \gamma_i)}\right) B_{i,k}}{N_k} \tag{3}$$

where P_i is the price of species i and N_k denotes the total number of fishing trips to area k per unit time period. It is easy to see from (3) that the average revenue will increase with fish prices and initial stock, and decrease with the number of trips.

We assume that all boats that target the same species (tuna or swordfish) are identical and that once the boat reaches a fishing location k, they expend the same fishing effort (e.g., number of hooks per day over an equal number of days). The assumption of identical effort across boats targeting tuna or swordfish may be reasonable for an industry with homogeneous gear (e.g., longliners) in which most boats would have roughly similar storage capacity for bait and har-

vested fish. Second, the time spent fishing may be limited since the quality of the freshly harvested fish on board begins to decline rapidly with time.

Let FD denote the number of fishing days per trip. Since each boat can change types (e.g., targeting swordfish or tuna) during a single trip, $FD = \sum_s FD_{k,s}$, where $FD_{k,s}$ is the number of days a boat is of type s per trip in area k. It implies that the numbers of days a boat chooses to target tuna or swordfish may vary but the total number of fishing days per trip is fixed. The allocation of set type within a trip is a choice variable. Let $\overline{E}_s$ denote the amount of fishing effort (sets of 1,000 hooks per day) by a boat of type s, which is constant. Then the aggregate amount of fishing effort in area k by set type s, is

$$E_{k,s} \equiv \overline{E}_s \cdot FD_{k,s} \cdot N_k \tag{4}$$

Cost Structure and Crew Wage

We assume risk neutrality on the part of boat owners and crew but incorporate features of the labor-employment relation that have a bearing on apportioning of revenue and costs from fishing (Plourde and Smith, 1989). For this purpose, we classify the costs of fishing into two categories: fixed and variable (i.e., operational) costs. In the share system that is prevalent in the Hawaii longline fishery (Hamilton, Curtis, and Travis, 1996), fixed costs are usually borne by the vessel owner and consist of overhead expenses (e.g., maintenance, mooring, and depreciation charges) which do not depend directly on the fishing trip and are more or less fixed on an annual basis. Therefore, we assume that fixed costs do not affect the trip allocation decision in our short run model.

The variable costs are the expenses incurred during the fishing trip (e.g., fuel, bait and gear). This can be further broken down into costs incurred while traveling to area k and fishing in that location. We assume away travel costs within area k, which may be reasonable because they are likely to be a small fraction of the costs of traveling from port. For simplicity, each trip involves direct travel to the chosen destination and return to port, i.e., fishing at multiple locations within the same trip is not allowed. In addition there is an auction fee that is levied as a percentage of the total catch. These variable costs are shared equally by the owner and crew. The owner is usually absentee while by crew we denote all hands on board including the captain. The net revenue from a trip to area k, NR_k is

$$NR_k = AR_{Trip,k}(1-\tau) - \left(\sum_s a_s \cdot FD_{k,s} + b \cdot TD_k \right) \tag{5}$$

where cost parameters a_s and b represent the average daily variable costs of fishing with set type s and traveling, respectively and TD_k is the number of days spent in traveling from port to destination k and back. As mentioned before, since all boats spend an equal number of fishing days per trip, the total number of fishing days per trip FD is equal across trips. On the other hand, the number of travel days TD_k can be estimated by dividing twice the distance to area k from port by the average vessel speed.

The incomes accruing to the vessel owner and crew from a trip to area k are given by

$$OI_k = (1-\lambda)\cdot NR_k \tag{6}$$

and

$$CI_k = \lambda \cdot NR_k \tag{7}$$

where OI_k and CI_k and $(1-\lambda)$ and λ denote the respective incomes and relative shares of net revenue accruing to the owner and crew.

The crew income from a trip in (7) or the crew wage per day, which is the crew income divided by the total number of trip days, may be used as a measure of wage. However, both indicators may be biased when comparing wages across fishing areas due to the variation in the distance of the fishing location from port. We remove this bias by normalizing wages with respect to distance employing a procedure detailed in Appendix 1 which yields NCW_k, the normalized crew wage for a trip to area k. Finally, let NCW denote the weighted average normalized crew wage for the entire fishery per unit time period, obtained as

$$NCW = \frac{\sum_k NCW_k \cdot N_k}{\sum_k N_k}. \tag{8}$$

Finally, labor allocation per period in the fishery, measured in vessel-days, is obtained by summing both fishing and traveling days over all trips to all fishing areas as

$$VD = \sum_k (FD + TD_k) N_k \tag{9}$$

where VD is the aggregate amount of labor allocation in vessel-days per time period.

Given exogenous fish prices, a derived demand function for labor is obtained through optimal allocation of vessel trips over space. Since vessels are assumed identical in every respect, it is straightforward to distribute the representative vessel trip spatially starting from the fishing location that yields the maximum normalized crew wage to the crew (i.e., NCW_k). Note that the allocation of sets (tuna and swordfish) within each trip is endogenous. As vessels get assigned to locations generating maximum normalized crew wage, subsequent harvests in that location decline because of stock externality. Other competing fishing locations become more profitable. Thus as the aggregate number of trips - all of which consist of an equal number of fishing (though not travel) days - increases, the marginal, and hence the average trip wage decreases. Because of the discrete nature of the problem of allocating a fixed number of vessel trips, the equilibrium normalized crew wage will only be approximately equal across locations. Thus in a model where the number of boats is infinitely divisible, NCW_k and NCW are exactly equal. A plot of the normalized wage index as a function of aggregate industry effort (vessel-days) yields a downward sloping derived demand function for labor. Note that this demand function may shift in response to changes in fish prices or the initial distribution of the fish stock.

Labor Supply and Equilibrium Allocation of Trips Over Space

The fishing industry is ideally suited for modeling the labor supply behavior of fishermen. This is because most fishermen are self-employed and boat captains generally have the power to decide if and when to undertake a fishing trip and for how long. Furthermore, as pointed out by Gautam, Strand and Kirkley (1996), unlike other professions in which labor and leisure activities coexist almost on a daily basis, commercial fishing in the high seas is demanding work coupled with limited leisure opportunities. This makes the disutility of spending another day fishing or staying at sea an important determinant of the labor supply decision. Assuming a fixed number of fishing vessels, the aggregate labor supply function can be expressed as

$$VD = S_L\left(NCW, M\right) \tag{11}$$

where M is income from non-fishing activities. Labor supplied by the crew (including captain) is expected to increase with the normalized crew wage NCW and it may in the short run exhibit backward-bending properties (as in Gautam, Strand and Kirkley, 1996). In general, non-fishery income M may affect the labor-leisure substitution. However, for commercial fisheries as considered here, M may be relatively small, and in any case it is difficult to obtain data for non-fishery income earned by fishermen. It is therefore ignored in the empirical estimation.

In order to econometrically estimate the labor supply function in (11), we obtain NCW and VD using actual data (Kennedy, 1992). That is, the actual numbers of catches and vessel trips to area k are used in (3) as compared to the use of equations (1-10) in the calculation of the derived demand function obtained from stock and price data.

Note that the derived demand function for labor is expected to shift in response to changes in fish prices or the distribution of fish stocks, while the labor supply function remains constant across periods. Finally, the equilibrium levels of NCW and VD are obtained by equating the derived labor demand with the estimated labor supply function from (11).

3. APPLICATION TO THE HAWAII LONGLINE FISHERY

In this section we apply the above model to the Hawaii longline pelagic fishery. The Hawaii commercial fishery has rapidly grown since 1987 with annual commercial value estimated at roughly $60 million (WPRFMC, 1997). Longline vessels account for more than 80 percent of gross revenue, the remaining being from baitboat (pole-and-line skipjack), handline and trolling. For the purposes of this study, we only deal with longline vessels which are reasonably homogenous in terms of fishing technology and other vessel characteristics. The major species targeted by the longline fishery are broadbill swordfish and bigeye tuna (He, Bigelow, and Boggs, 1997) while yellowfin and albacore tunas and striped marlin also represent a significant share of the total ex-vessel revenue. Together these five species of fish, accounted for approximately 90% of gross revenue in 1995.

We construct a spatial grid that divides the fishery into 56 five-by-five degree (latitude and longitude) squares centered in the Main Hawaiian Islands (MHI). These areas are located between latitude 5°N to 45°N and longitude 140°W to 170°E. Each five-degree square is defined using its southeast corner as the reference point, e.g., the square between latitudes 15° and 20° N and lon-

gitudes 140° and 145°W is labeled as *15N140W* (as per a classification system developed by Curran, Boggs, and He, 1996).

Catch and fishing effort data from the 1995 longline logbook, collected by the National Marine Fisheries Service (NMFS) (Dollar and Yoshimoto, 1991) are aggregated by five-by-five degree square and by month. The data suggest that 1,125 trips (corresponding to 11,129 sets and about 13.3 million hooks) were taken by 110 active longline vessels in 1995 (WPRFMC, 1997). That is, on average each longline fishing trip lays approximately 10 sets – one set each fishing day.

Swordfish vs Tuna Sets

One complication that needs to be considered in empirical work is the targeting strategy of the vessel. That is, each boat can target swordfish on any given fishing day, or it may target tuna (bigeye and yellowfin) while the remaining two species albacore and striped marlin are caught mainly as by-catch. Targeting these distinct species imposes distinct fishing and cost characteristics on the boat. For example, swordfish sets are soaked overnight and they use more expensive bait (squid) and other devices (light sticks). Tuna sets are soaked in daylight, and use cheaper samma (saury, *Cololabis saira*) as bait. The catchability coefficients (from (1)) would be different for each set since swordfish (tuna) targeting would lead to bigger swordfish (tuna) catches, *ceteris paribus*. Allocation of sets is done by inspecting logbook data and designating each set as swordfish or tuna set depending on whether they satisfy the above qualitative criteria. About 11 percent of the sets did not fall clearly into any category – e.g., a set that soaked in the night, used squid as bait but did not use any light sticks. These were allocated by looking at which of the above criteria they matched more closely.

Given the two fishing strategies or set types, the specification of the instantaneous fishing mortality rate in (2) can be simplified as

$$f\left(E_k,\gamma_i\right)=\gamma_{i1}\,E_{k1}+\gamma_{i2}\,E_{k2} \tag{12}$$

where subscripts 1 and 2 denote tuna and swordfish sets respectively. Since the average number of hooks used in a swordfish set (820) was different from a tuna set (1,498), the fishing effort levels in area k by type 1 and 2 can be expressed from (4) as $E_{k1}=1.498\ FD_{k1}\cdot N_k$ and $E_{k2}=0.820\ FD_{k2}\cdot N_k$. Here $\left(FD_{k1}\cdot N_k\right)$ and $\left(FD_{k2}\cdot N_k\right)$ represent the total numbers of tuna and swordfish sets conducted in area k and $FD_{k1}+FD_{k2}=10$ since the sum of swordfish and tuna sets per trip must equal the total fishing days, and we define one unit of fishing effort as 1,000 hooks.

Estimating Catchability Coefficients and Fish Stocks

Given the two distinct fishing strategies, two sets of catchability coefficients for each species (i.e., for tuna and swordfish sets) are estimated from monthly catch and effort data, details for which are given in Appendix 2. The results are summarized in Table 1. The catchability for swordfish with a tuna set was very low (0.0002) which implies that a tuna set catches very few swordfish. Also for a given stock size and unit effort, a swordfish set catches 22 times more swordfish than a tuna set. The table also suggests that a swordfish set catches more bigeye and

yellowfin tuna than even a tuna set, although fishermen may actually prefer to catch these tunas using the cheaper cost of a tuna set. Okamoto (1999) obtained similar results, where catches of albacore and striped marlin were higher from tuna sets than from swordfish sets, while swordfish catches from swordfish sets were higher than those from tuna sets.

TABLE 1
Estimation Results for Catchability Coefficients by Species and by Fishing Strategies

Species	Catchability coefficient		Catchability ratio
	Tuna set (γ_{i1})	Swordfish set (γ_{i2})	(γ_{i1}/γ_{i2})
Swordfish	0.00022	0.00483	22.453
Bigeye Tuna	0.00338	0.00738	2.181
Yellowfin Tuna	0.00378	0.01224	3.237
Albacore Tuna	0.00431	0.00058	0.135
Striped Marlin	0.00248	0.00195	0.788

The catchability coefficients for the five major species as well as monthly effort and catch data are used to estimate the initial size of the monthly fish stock $B_{i,k}$ in each location from (1). That is, the estimated fish stock (population of species i in location k) is assumed to be "in place" at the beginning of each month but depletes with harvesting as trips are allocated at each location. A new stock is estimated at the beginning of each month. In one sense, the model simplifies the inflow and outflow of fish migration in each grid by assuming that migration could only occur instantaneously at the point of transition between successive time periods, i.e., at the beginning of each calendar month. Notice that a calendar month is only an arbitrary device, and the model could be built with weekly price, catch and effort data, if available, although allocation of trips which usually last longer than a week, may be problematic in that situation.

Expected Revenue from a Trip

Monthly fish prices are assumed to be exogenously determined since most of the fish is sold in markets in Japan and in the U.S. mainland (WPRFMC, 1995). Prices were computed using revenue data for each species collected by the Hawaii Department of Agriculture and Resources (HDAR). Catch data is in terms of numbers of fish caught and fish prices are in dollars per standard-sized fish, as shown in Figure 1. Using (3), expected revenue in each location was computed from fish prices and estimated stocks. Since the aggregate revenue from the five major species was 92.82 percent of the total revenue reported in 1995, a correction factor of 1.0774 was applied to account for other minor species and side catches.

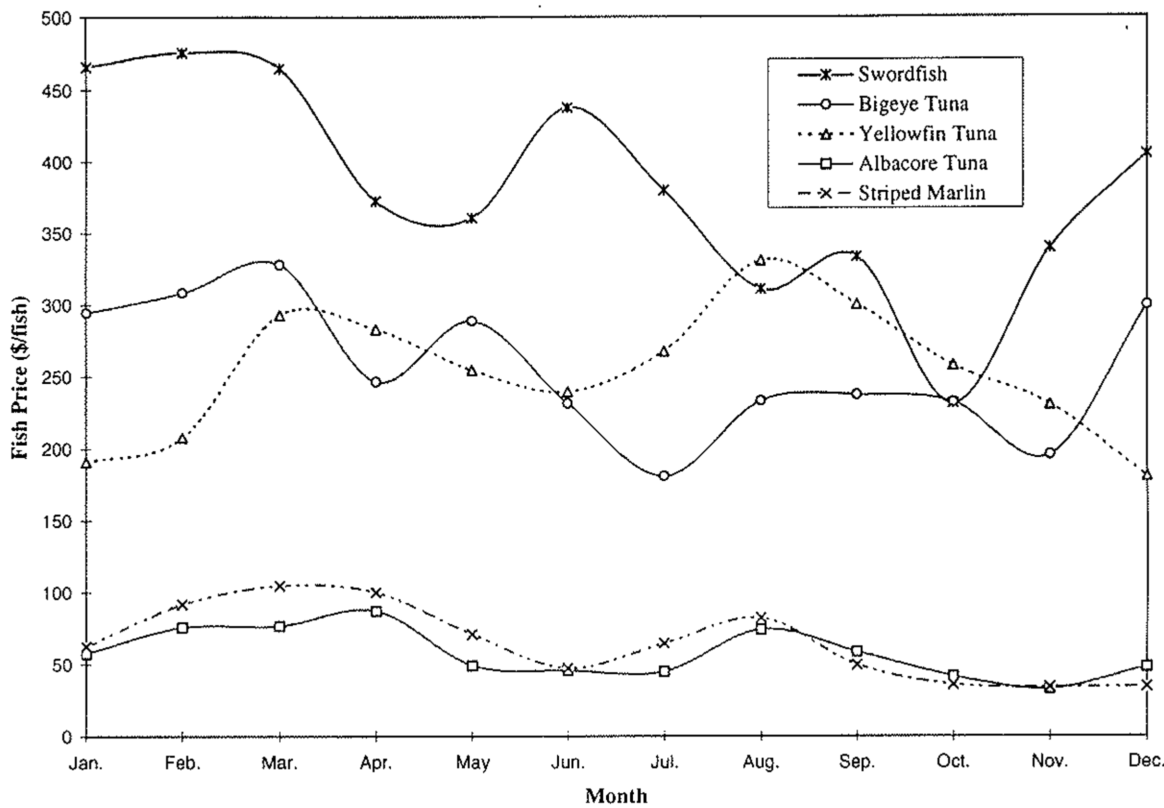

Figure 1. Average Monthly Fish Prices ($/fish)

Variable Costs of Fishing

As mentioned earlier, we ignore fixed costs of fishing and focus only on variable costs and taxes. Both the auction fee and the excise tax are shared equally between the owner and crew and are a fixed proportion of gross trip revenue. In Hawaii, longliners are legally obliged to sell their catch to the United Fishing Agency Ltd. which charges each vessel an auction fee equal to 10% of the total revenue from a fishing trip. The excise tax rate is an additional 0.5% of the total revenue (Hamilton, Curtis, and Travis, 1996).

Variable costs, including the cost of food, oil, fuel, bait, light-stick, ice, and miscellaneous gear, can be broken down according to their relationship to fishing or traveling activity. Food, oil, and fuel are consumed for both, while expenses on bait, light-sticks, ice, and miscellaneous fishing gear occur only during fishing. Table 2 details the breakdown of the variable cost. Based on the survey by Hamilton, Curtis, and Travis (1996), the average daily costs for food and oil are $81.54 and $9.41 respectively. The cost of fuel is on average higher on a travel day than on a fishing day; i.e., the average fuel cost was $219.11 for fishing days and $250.56 for travel days.

TABLE 2
Estimated Average Daily Variable Costs ($/day)

Items	Fishing day		Traveling day
	Tuna set	Swordfish set	
Food	81.54	81.54	81.54
Oil	9.41	9.41	9.41
Fuel	219.11	219.11	250.56[a]
Ice	85.50	39.10	
Bait	272.88	652.42	
Light-stick	0.00	529.13	
Misc. gear	111.40	531.90	
Total	779.84	2062.61	341.51

Source: Hamilton, Curtis, and Travis (1996)
[a] In their survey, 37 out of 94 vessels surveyed found no fuel cost differentials between fishing and traveling days, 9 reported higher fuel costs for fishing days, and the remaining 48 vessels reported higher fuel costs for traveling days. The average fuel cost was $219.11 per fishing day and $250.56 per traveling day.

Another complication is the calculation of variable costs is the higher expense of targeting swordfish relative to the tuna species (i.e., bigeye and yellowfin). The average variable cost per fishing day (out of the 10 fishing days in a trip) depends on the proportion of swordfish-targeted sets in the standardized 10 sets of fishing effort. As indicated in Table 2, the cost of a fishing day is much higher than the cost of a travel day, and swordfish fishing is almost thrice as expensive as tuna fishing. This yields the following formula for variable costs for a trip to area k:

$$VC_k = \left(779.84 + 1282.77 \times r_{sw}\right) \times 10 + 341.51 \times TD_k \tag{13}$$

where r_{sw} is the share of swordfish sets in the total. The above equation implies that the respective daily costs for a tuna and swordfish set are about $780 and $2063, due to more expensive bait, lightsticks and miscellaneous gear in the latter.

Net Return and Normalized Crew Wage

The net return for a trip to area k, and the normalized crew wage can then be expressed as

$$NR_k = \frac{\sum_i P_i \left(1 - e^{-(\gamma_{i1} E_{k1} + \gamma_{i2} E_{k2})}\right) B_{i,k}}{N_k} \times 1.0774 \times (1 - 0.105) - VC_k \tag{14}$$

and

$$NCW_k = \frac{0.50 \times NR_k}{10 + 0.3804 \times TD_k} \tag{15}$$

where 0.105 is the total share of revenue paid out as auction fee (10%) and excise tax (0.5%), 0.3804 is the ratio of wages from a travel day relative to a fishing day (see Appendix 1), and the

vessel owner and crew each collect 50% of the residual profit (i.e., $\lambda = 0.50$) – more than 95% of Hawaii-based longline vessels follow the equal sharing rule (Hamilton, Curtis, and Travis, 1996). These equations yield the derived demand for labor as explained in the previous section.

Estimation of Labor Supply

To get the supply function, the monthly total revenue from trips to area k was estimated using actual catch data by region from the 1995 longline logbook. Unfortunately, logbook data does not reveal the number of trips made by vessels to a specific location, only the total numbers of sets and hooks placed in each square by month. Since we assume that the exact 10 sets must be conducted in a single fishing location within a trip, dividing the total number of sets placed in each square by 10 yields the "actual" number of trips. The number of vessel-days, computed from (10), were aggregated by month, and are summarized in Table 3. The annual number of trips approximated thus was 1,165, somewhat larger than the 1,125 total longline trips made in 1995 (WPRFMC, 1997). One reason for this overestimation was that vessels tended to conduct more sets during distant-water fishing trips. Part of the error could also be due to errors in recording of logbook data.

TABLE 3
Data for Estimating the Fishing Effort Supply

Month	Number of fishing trips[a]	Fishing effort (vessel-days)	Normalized crew wage ($/day)	Total ex-vessel revenue of longline industry (million $)
Jan.	99.1	1,687	1,142	4.34
Feb.	99.3	1,913	1,106	4.72
Mar.	102.5	1,861	1,079	4.76
Apr.	104.5	2,003	636	3.78
May.	120.3	2,052	540	3.76
Jun.	105.4	1,971	624	3.63
Jul.	87.6	1,604	329	2.37
Aug.	61.3	1,289	162	1.33
Sep.	64.5	1,225	129	1.16
Oct.	90.3	1,382	437	2.05
Nov.	111.7	1,878	445	2.80
Dec.	118.2	2,047	801	4.12
Total	1164.7	20,913	619	38.80

Source: Computed from 1995 National Marine Fisheries Service (NMFS) logbook data.
[a]Actual aggregated number of sets divided by 10 fishing days per trip

To derive the supply function, a simplified specification of a labor supply function used by Battalio, Green and Kagel (1981) was estimated as follows:

$$\ln VD = 2.2918(\ln NCW) - 0.17392(\ln NCW)^2, \qquad (16)$$
$$(45.03) \qquad\qquad (21.89)$$

where numbers inside the parentheses are t-ratios. The resulting adjusted R^2 and Durbin-Watson statistic were 0.6731 and 2.305 respectively. Both parameters were significant at the 1% level. Since the crew would not go fishing if the expected wage is not high enough, $\ln VD \leq 0$ when $\ln NCW = 0$, the intercept in (16) should be zero or negative. Because a positive but insignificant intercept was obtained in the preliminary estimation, the intercept was restricted to zero. The labor supply function obtained is illustrated in Figure 2. Supply is increasing with NCW when $NCW <$ \$727/day, but it is backward-bending at higher values.

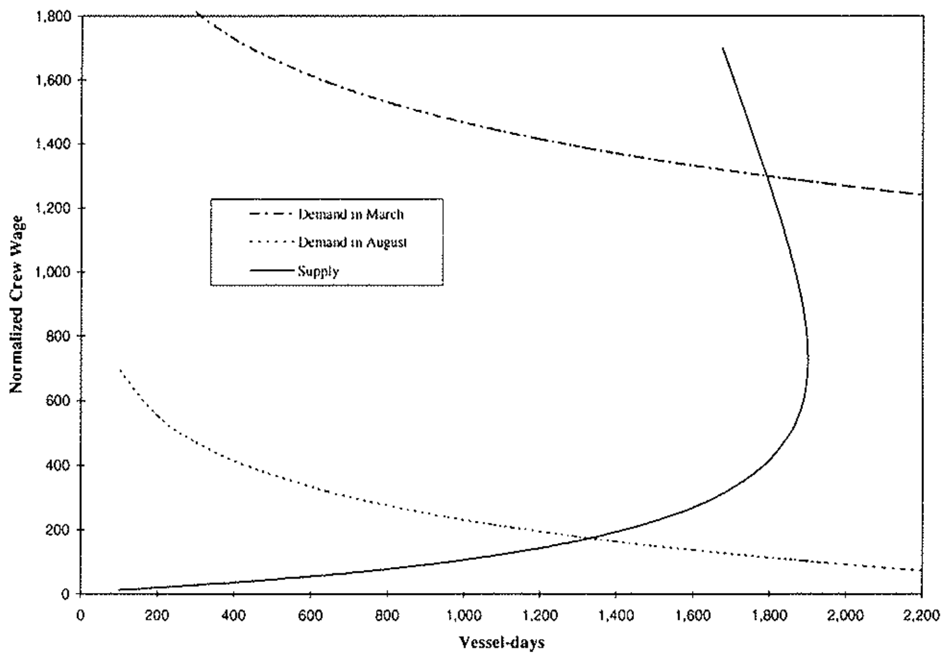

Figure 2. Derived Demand (in March and August) and Supply Curves for Effort

Ex-vessel revenues from the five major species shows that the longline industry earned more than \$4 million per month during the first quarter and in December, and much less during the other months, particularly from July to November. The above data indicate that the backward-bending supply curve may be reasonable.

Simulating the Hawaii Longline Fishery

Equilibrium monthly effort allocation that equates demand and supply of effort for the entire fishery is determined using a simulation algorithm written in the programming language Turbo C++. Note that there are 12 different demand functions since stocks and prices vary by month but only a single estimated supply function. Results are only shown for March and August 1995, when the derived demands for labor are respectively large and small, are shown in Figure 2.

Model results for the baseline year 1995 are compared with the actual distribution of effort in the Hawaii longline fishery, shown in Figure 3. In order to investigate the importance of the leisure-

labor tradeoff in the estimation of the supply function, an alternative model in which there is no income effect on the consumption of leisure (i.e., days on shore) is also presented in the figure. The later model ignores the fisherman's disincentive to supply effort brought on by higher trip wages. Without this effect, the supply curve is horizontal; that is, fishing trips are allocated until labor demand is equal to the normalized crew wage computed from 1993 wage data (Hamilton, Curtis, and Travis, 1996). As shown in Figure 3, the model without the labor-leisure tradeoff demonstrated poor fitness. For example, the number of trips allocated was overestimated in the first quarter (particular in March) when trip revenue is relatively high (Table 3) due to higher fish prices and stock abundance, and underestimated during April to November (no trips were allocated during August and September) when trip revenue was relatively low. This suggests that overestimation may have been caused because the disincentive to supply effort when crew wages were high in the first quarter was ignored. This comparison suggests that incorporation of the leisure-labor tradeoff may be significant in modeling fishermen's behavior as suggested by Gautam, Strand and Kirkley (1996).

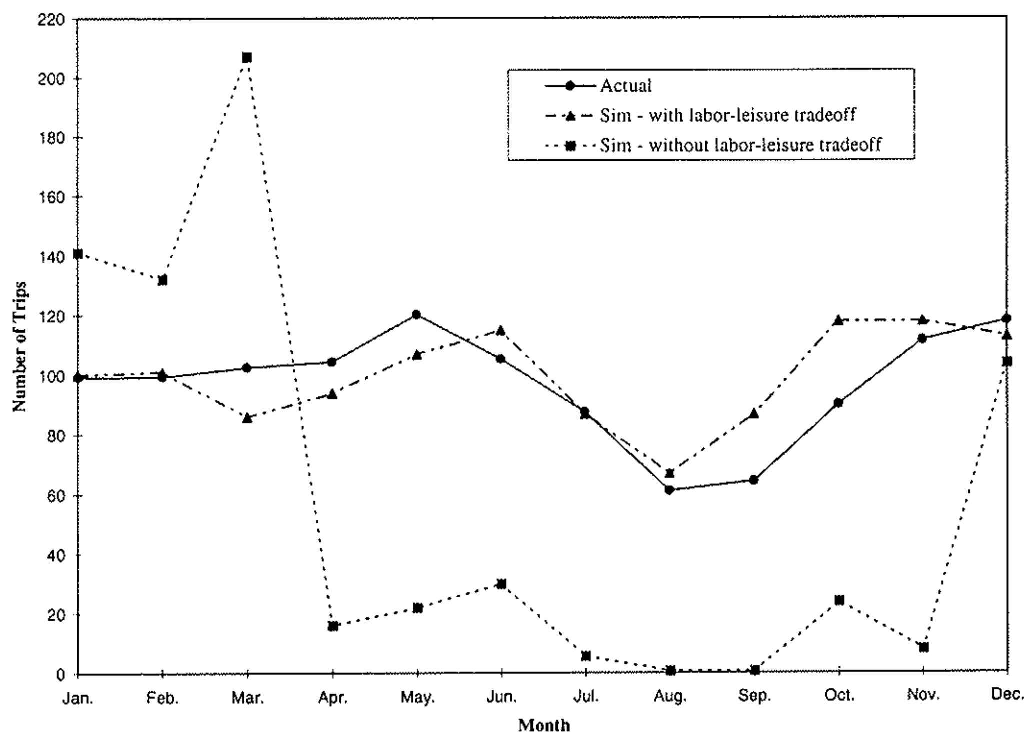

Figure 3. Number of Allocated Fishing Trips, 1995: Actual and Simulated (With and Without the Labor-Leisure Tradeoff)

On the other hand, the model with the labor-leisure tradeoff performs markedly better in tracking the actual allocation of boats. The Mean Absolute Percentage Error (MAPE) was 11.4%, while that for the case without the labor-leisure tradeoff was more than 70%. However, gaps between the actual and predicted number of trips still remain, as shown in Figure 3. The simulated number of trips is somewhat underestimated from March to May, and overestimated from September to November.

A large part of the difference can be explained by the difference in the number of swordfish sets from optimization and the actual spatial distribution as shown in Table 4. For instance, in March and April, only 7 trips are allocated to two fishing regions near the Main Hawaiian Islands (MHI: *20N155W* and *15N155W*) although more than 40 trips were allocated in reality. However, relatively more trips are allocated in other areas, such as north of 30°N. On the other hand, from September to November, 47 more trips are allocated to the two MHI regions in the simulation while 30 less trips are allocated to the regions north of 30°N.

TABLE 4

Monthly Fishing Effort Allocation and Normalized Crew Wage: Actual vs. Simulated

	Allocation of Trips						
Month	MHI[a] (20N155W & 15N155W)	5° N - 30° N excluding 2 MHI areas	North of 30° N	All areas	Effort in vessel-days (*VD*)	Ratio of swordfish sets	Normalized crew wage (*NCW*)
				Actual			
Jan.	32.5	47.4	19.2	99.1	1,687	34.3%	1141.60
Feb.	17.6	46.5	35.2	99.3	1,913	42.8%	1105.75
Mar.	23.7	58.5	19.8	102.0	1,861	45.9%	1079.24
Apr.	18.3	79.4	6.8	104.5	2,003	52.6%	635.80
May.	36.3	83.7	0.3	120.3	2,052	52.0%	540.07
Jun.	22.0	82.3	1.1	105.4	1,971	53.7%	623.76
Jul.	26.0	55.2	6.4	87.6	1,604	59.6%	329.12
Aug.	20.7	24.3	16.3	61.3	1,289	52.4%	162.31
Sep.	12.1	40.5	11.9	64.5	1,225	43.4%	129.29
Oct.	40.8	39.3	10.2	90.3	1,382	25.5%	437.22
Nov.	52.8	37.5	21.4	111.7	1,878	30.3%	445.21
Dec.	16.1	79.5	22.6	118.2	2,047	32.0%	801.21
Total	318.9	674.1	171.2	1164.2	20,913	43.3%	619.21
				Simulated			
Jan.	23	48	29	100	1,857	32.5%	1029.04
Feb.	21	51	29	101	1,852	30.2%	977.87
Mar.	2	62	22	86	1,796	40.7%	1239.35
Apr.	5	80	9	94	1,863	54.1%	540.63
May.	33	74	0	107	1,833	64.9%	487.34
Jun.	27	87	1	115	1,841	68.6%	499.39
Jul.	20	43	24	87	1,664	35.2%	323.04
Aug.	36	9	22	67	1,329	29.3%	178.69
Sep.	25	56	6	87	1,379	0.0%	188.08
Oct.	63	48	7	118	1,690	0.0%	335.91
Nov.	65	52	1	118	1,706	0.0%	340.47
Dec.	2	96	15	113	1,885	15.9%	876.70
Total	322	706	165	1193	20,694	30.6%	584.71

[a] Main Hawaiian Islands

Part of the error may be due to the fact that vessels tend to fish in familiar locations, not necessarily in those which return maximum profits. There is also the difficulty of estimating catches for each species, as seen in the species-wise breakdown of actual and simulated catches given in Table 5. It shows that the simulated aggregate catch of albacore and striped marlin were higher by more than 20%, although the error margins for the other three major species (i.e., swordfish, and bigeye and yellowfin tunas) was less than 10%. One possibility is that fishermen may not be explicitly incorporating revenues from albacore and striped marlin in their decision-making process because these two are somewhat "undesirable" species, much less valuable than the other three and take up scarce storage space in vessels (Kelleher, 1997).

TABLE 5
Catches of Five Species in the Hawaii Longline Fishery:
Actual vs. Simulated (Baseline Case)

	Swordfish			Bigeye			Yellowfin		
Month	Actual[a]	Sim.[a]	%Error[b]	Actual	Sim.	%Error	Actual	Sim.	%Error
Jan.	2,821	3,646	29.2%	7,838	7,393	-5.7%	2,218	2,322	4.7%
Feb.	4,299	3,916	-8.9%	5,971	6,403	7.2%	2,333	2,365	1.4%
Mar.	3,855	3,851	-0.1%	6,607	7,130	7.9%	2,432	1,969	-19.1%
Apr.	5,446	5,384	-1.1%	4,004	2,633	-34.2%	1,675	1,308	-21.9%
May	4,500	5,296	17.7%	4,834	3,954	-18.2%	1,706	1,568	-8.1%
Jun.	4,625	5,667	22.5%	3,251	2,934	-9.8%	2,425	2,511	3.5%
Jul.	2,846	3,280	15.2%	1,266	1,101	-13.0%	3,159	2,561	-18.9%
Aug.	1,320	1,394	5.6%	1,600	2,166	35.4%	1,144	990	-13.5%
Sep.	771	106	-86.3%	2,276	2,718	19.4%	774	820	5.9%
Oct.	774	294	-62.0%	5,533	6,581	18.9%	1,244	1,112	-10.6%
Nov.	1,742	229	-86.9%	6,853	8,082	17.9%	1,381	1,408	2.0%
Dec.	2,463	1,833	-25.6%	8,075	8,531	5.6%	2,461	2,149	-12.7%
Total	35,462	34,896	-1.6%	58,108	58,626	2.6%	22,954	21,083	-8.2%

	Albacore			Striped Marlin		
Month	Actual	Sim.	%Error	Actual	Sim.	%Error
Jan.	1,888	3,701	96.0%	1,858	1,621	-12.8%
Feb.	1,753	3,108	77.3%	1,229	1,381	12.4%
Mar.	2,538	4,286	68.9%	1,334	1,053	-21.1%
Apr.	2,230	6,373	185.8%	984	569	-42.5%
May	4,213	3,474	-17.5%	2,020	1,938	-4.1%
Jun.	6,000	5,681	-5.3%	1,209	1,899	57.1%
Jul.	3,696	5,094	37.8%	529	733	38.6%
Aug.	2,012	2,215	10.1%	249	375	50.6%
Sep.	2,300	5,228	127.3%	1,706	3,031	77.7%
Oct.	5,543	6,057	9.3%	2,704	3,364	24.4%
Nov.	4,572	3,653	-20.1%	2,903	3,946	35.9%
Dec.	1,776	397	-77.6%	4,506	5,668	25.8%
Total	38,521	49,267	27.9%	21,231	25,575	20.5%

[a] Data are in units of standard-size fish.
[b] %Error = [(simulated catch) - (actual catch)] / (actual catch)

Some other factors that may contribute to the difference in results are (i) the assumption of identical vessels in terms of cost structure, speed, and other parameters such as the number of lightsticks used per fishing set, (ii) perfect knowledge about fish prices and stocks in each fishing location, (iii) the assumption of costless switching between tuna and swordfish sets, and (iv) restriction to one fishing location per trip. In particular, certain group of vessels use only one strategy (tuna or swordfish) for a long period of time due to factors such as personal preference and other vessel-related physical constraints.

4. POLICY SIMULATION

We use the model to examine the economic impacts of three proposed regulatory policies: (i) the closure of two five-degree squares, including the fishing areas off the main Hawaiian islands to avoid gear conflicts (ii) closure of all fishing areas north of 30°N for sea turtle conservation, and finally (iii) increase of auction fee from 10% to 20% for revenue generation.

Reducing Gear Conflict: Closure of Areas near the Main Hawaiian Islands (Case 1)

Limited entry restrictions such as area closure, are particularly appropriate in reducing short-run (or crowding) externalities (Townsend, 1990). Several gear types often compete for the same species of pelagic fish and hence the exclusion of a particular gear type would reduce crowding. In Hawaii, longline and surface fleets (trollers and handliners) have often fished in the same locations, especially within 20 nautical miles of the shore (Skillman, Boggs, and Pooley, 1993). Historically, longline vessels have been excluded from fishing in certain regions from time to time. In recent years, troll and handline landings of several pelagic species (e.g., yellowfin) have declined substantially, while longline landings have increased (Pooley, 1994). Other small commercial, charter, subsistence and recreational boats operating near-shore have also been adversely affected.

We examine the impact of the year-round closure of two areas, *20N155W* (including Oahu and Maui) and *15N155W* (including a major part of the fishing areas close to the Big Island). The results are summarized in Table 6. The importance of the closed areas can be seen from column A in the Base Case – for example, in August, October and November, more than 50% of the effort was centered on the two closed squares. The column (C - B) in Table 6 shows the substitution of vessels into other areas as a result of area closure. Vessels compensate by fishing in distant waters, which results in an increase in costs and reduced wages as summarized in Table 9. The aggregate number of trips declined. Originally 322 trips were made into the closed areas, but with the closure policy, only 180 were reallocated, leading to a net decrease in 142 trips out of the original 1192 trips - a decline of about 12 percent.

TABLE 6
Trip Allocation With and Without Area Closure:
Closure of Two Five-degree Squares *20N155W* and *15N155W*

	Base Case			Area Closure		
Month	Closed areas (A)	Other areas (B)	All areas (A + B)	Other areas[a] (C)	Change in other areas (C - B)	Change in all areas (C - A - B)
Jan.	23	77	100	94	+17	-6
Feb.	21	80	101	95	+15	-6
Mar.	2	84	86	85	+1	-1
Apr.	5	89	94	92	+3	-2
May	33	74	107	92	+18	-15
Jun.	27	88	115	106	+18	-9
Jul.	20	67	87	79	+12	-8
Aug.	36	31	67	43	+12	-24
Sep.	25	62	87	75	+13	-12
Oct.	63	55	118	87	+32	-31
Nov.	65	53	118	91	+38	-27
Dec.	2	111	113	112	+1	-1
Total	322	871	1193	1051	+180	-142

[a]The number of trips allocated to "closed areas" is zero.

Conserving Sea Turtles: Closure of the North Fishing Areas North of Latitude 30°N (Case 2)

Interaction between longline gear and endangered species such as sea turtles is continuously reported in the logbook data (Ito, 1995). Leatherback, green sea, loggerhead, and olive ridley turtles were reported to have been accidentally caught a total of 84 times during 1994, although these interactions are widely believed to be under-reported. Kleiber (1998) estimates that approximately 700 sea turtles were taken and around 100 were killed in 1995. Most of the loggerhead and leatherback turtles were caught in the areas north of 30°N. Fishery biologists such as Nitta and Henderson (1993) have suggested the closure of fishing areas north of 30°N to conserve sea turtles. The impacts of such a policy are simulated in Table 7. Unlike the previous case, turtle conserving policies confine longline vessels to fishing areas closer to Hawaii, i.e., below 30°N. Since more vessels now fish inshore, travel days decrease, which in turn enables more trips to be taken. Thus, aggregate number of trips shows a small increase. The ratio of swordfish sets to the total falls from 31% to 20%, and hence swordfish catches, which mostly occur in the high seas, decline significantly (40 %) causing normalized crew wages to fall by 9.4% (Table 9).

TABLE 7
Trip Allocation With and Without Area Closure:
Closure of All Five-Degree Squares North of 30°N

	Base Case			Area Closure		
Month	Closed areas (A)	Other areas (B)	All areas (A + B)	Other areas[a] (C)	Change in other areas (C - B)	Change in all areas (C - A - B)
Jan.	29	71	100	115	+44	+15
Feb.	29	72	101	114	+42	+13
Mar.	22	64	86	90	+26	+4
Apr.	9	85	94	97	+12	+3
May	0	107	107	107	0	0
Jun.	1	114	115	116	+2	+1
Jul.	24	63	87	98	+35	+11
Aug.	22	45	67	72	+27	+5
Sep.	6	81	87	90	+9	+3
Oct.	7	111	118	121	+10	+3
Nov.	1	117	118	119	+2	+1
Dec.	15	98	113	122	+24	+9
Total	165	1028	1193	1261	+233	+68

[a]The number of trips allocated to "closed areas" is zero.

Increasing Auction Fee From 10% to 20% (Case 3)

Increase in the auction fee may serve as a mechanism not only to reduce the profitability of fishing and thereby preserve fish stocks but also as a means of generating additional revenue for the State. We thus examine the impacts of an increase in the auction fee rate from 10% to 20% (Table 8). Since the auction fee is a fixed percentage of total revenue before netting variable costs, increase in the fee results in a disproportionate negative effect on boats specializing in distant-water fishing whose variable costs tend to be higher. In particular, trips fishing north of 30°N are significantly affected (down by 31 trips), followed by those fishing between 5°N and 30°N, as shown in Table 8.

TABLE 8
Trip Allocation with Baseline (10%) and Increased (20%) Auction Fee

Month	Base case: MHI[a] (20N155W & 15N155W)	Base case: 5° N - 30° N excluding 2 MHI areas	Base case: North of 30° N	Base case: All areas	Changes from increasing auction fee to 20%: MHI[a] (20N155W & 15N155W)	Changes: 5° N - 30° N excluding 2 MHI areas	Changes: North of 30° N	Changes: All areas
Jan.	23	48	29	100	2	3	-2	3
Feb.	21	51	29	101	1	5	-2	4
Mar.	2	62	22	86	1	2	0	3
Apr.	5	80	9	94	3	3	-7	-1
May.	33	74	0	107	0	-5	0	-5
Jun.	27	87	1	115	-1	-4	0	-5
Jul.	20	43	24	87	0	-5	-1	-6
Aug.	36	9	22	67	2	2	-13	-9
Sep.	25	56	6	87	-2	-6	-3	-11
Oct.	63	48	7	118	-2	-3	-2	-7
Nov.	65	52	1	118	-3	-4	0	-7
Dec.	2	96	15	113	0	2	-1	1
Total	322	706	165	1193	1	-10	-31	-40

[a] Main Hawaiian Islands

It is counter intuitive that, because of the backward bending nature of the supply function, a higher auction fee increases the total effort level and the total number of trips when wages are higher especially in the first quarter and in December. Correspondingly, effort reduction will be higher with auction fee when labor supply is positively sloped, i.e., at low wage levels in the summer and fall (see Table 8).

Comparison of the Three Policies

The differential impacts of the three policies on trip allocation, employment, total revenue, government income through taxation, shared costs, profits and wages are summarized in Table 9. All three policies reduce industry revenue. The total revenue from all longline trips will decline under all three policies although the auction fee causes owner and crew incomes to decline significantly (21%). Annual income accruing to vessel owners is simply 50 percent of the fleet profit divided by the number of active vessels. Thus boat-owner incomes are most seriously affected by auction fees. Sustained low income may cause the net profit to fall below industry long-run average fixed cost, leading to exit from the industry. Some instances of exit from the Hawaii longline fishery to the U.S. Gulf Coast and Fiji have been observed in recent years (Travis, 1998).

TABLE 9
Comparison of Alternative Regulatory Policies:
(i) Reducing Gear Conflict, (ii) Sea Turtle Conservation, and (iii) Increasing Auction Fee

	Baseline Case	Case1[a] Gear Conflict	Case2[b] Turtle Conserv.	Case3[c] 20% Auction Fee
Trips and Effort:				
Number of Trips (A)	1,193	1,051	1,261	1,153
		(-11.9 %)	(+5.7 %)	(-6.3 %)
Effort in Vessel-Days (B)	20,694	19,428	19,038	19,655
		(-3.4 %)	(-1.9 %)	(-5.0 %)
Trip Length in Days per Trip (A / B)	17.3	19.0	16.1	17.0
		(+9.7 %)	(-7.2 %)	(-1.7 %)
Ratio of Swordfish Set	30.6%	35.7%	19.6%	26.0%
		(+16.6%)	(-36.0 %)	(-15.1%)
Revenue, Costs, and Taxes ($1,000):				
Industry Revenue (C)	38,611	35,515	36,039	36,822
		(-8.0 %)	(-6.7 %)	(-4.6 %)
Tax and Fee Revenue (D)	4,054	3,729	3,784	7,548
		(-8.0 %)	(-6.7 %)	(+86.2 %)
Shared Costs (E)	16,779	15,988	15,461	15,289
		(-4.7 %)	(-7.9 %)	(-8.9 %)
Fleet Profit (F = C - D - E)	17,778	15,797	16,793	13,984
		(-11.1 %)	(-5.5 %)	(-21.3 %)
Income and Wage ($):				
Boat-Owner Income per Vessel[d]	80,809	71,806	76,332	63,563
(F x 0.50 / 110)		(-11.1 %)	(-5.5 %)	(-21.3 %)
Crew Income per Trip (F x 0.50 / A)	7,451	7,515	6,659	6,064
		(-0.9 %)	(-10.6 %)	(-18.6 %)
Crew Wage per Day (F x 0.50 / B)	430	395	414	356
		(-11.9 %)	(-3.7 %)	(-17.2 %)
Normalized Crew Wage	585	542	530	465
		(-7.2 %)	(-9.4 %)	(-20.5%)
Catches (number of pieces):				
Swordfish	34,896	36,067	20,785	30,817
		(+3.4 %)	(-40.4 %)	(-11.7 %)
Bigeye Tuna	59,626	50,484	65,591	59,162
		(-15.3 %)	(+10.0 %)	(-0.8 %)
Yellowfin Tuna	21,083	17,165	24,320	20,933
		(-18.6 %)	(+15.4 %)	(-0.7 %)
Albacore Tuna	49,267	46,143	50,601	49,442
		(-6.3 %)	(+2.7 %)	(+0.4 %)
Striped Marlin	25,575	22,897	29,145	25,253
		(-10.5 %)	(+14.0 %)	(-1.3 %)

[a] Case 1: Two five-degree squares, 20N155W and 15N155W, are closed.

[b] Case 2: All five-degree squares north of 30°N are closed.

[c] Case 3: Auction fee is increased from 10% to 20%.

[d] 50% of the fleet profit divided by the number of active longline vessels (110) in 1995.

Crew incomes per trip are more negatively affected by turtle conservation (11%) and least by reducing gear conflict. However, this comparison is overstated because the average trip length is shorter under turtle conservation (boats fish closer to shore) than under gear conflict regulation. On the other hand, crew wages per day are more affected by gear conflict regulation (12%) than by turtle conservation. However, normalized crew wage, which is net of travel days, is least affected by gear conflict policies (7.2%), suggesting that turtle conservation has more of a negative impact on the crew than gear conflict policy.

The effect of alternative policies on conservation of fish stocks is also shown in the table. Interestingly, reduction of gear conflict leads to a significant reduction in catches for all the four species other than swordfish since they dominate harvests close to port. However, turtle conservation leads to a significant reduction of swordfish catches, but not in others. Rather, catches of bigeye and yellowfin tunas and striped marlin actually increase. Although an auction fee hike will mean more tax revenues, the impact on fish conservation is minimal since there is very little substitution of vessels across locations and the increased fees only helps in reducing net revenues.

5. CONCLUDING REMARKS

This paper develops a spatial and dynamic model of the allocation of fishing effort that explicitly incorporates the spatial distribution of multiple fish stocks, stock externalities from fishing and the relationship between fishing effort and crew wages normalized across fishing locations. The model is used to simulate the monthly allocation of effort in the Hawaii longline fishery for the year 1995. It is shown that estimation of a labor supply function significantly improves model prediction. The impact of regulatory decisions such as inshore (reduction of gear conflict) and offshore (reduction of turtle bycatch) area closures and taxes on harvest are examined. Inshore area closure leads to vessels moving to more distant waters. While vessel-owner's incomes decline significantly, the effect on crew income per trip is smaller since they benefit from taking longer trips. Catches of inshore species is significantly reduced. Offshore area closure policies reduce swordfish catches by about 40%. Average trip lengths decline by about 20% since boats fish closer to shore. On the positive side, substitution by boats into inshore areas and an increase in the number of trips allows for a relatively small adverse impact on fleet profits (5.5%). An increase in the auction fee on harvest succeeds in skimming profits from the fishery and nearly doubles tax revenues but has little effect on conservation of fish stocks.

These results could be useful in assessing the impacts of regulatory policy on industry groups or on conservation objectives (Wilen, 1993). There is an interesting asymmetry between the two area closure policies: reduction of gear conflict and turtle conservation. In the first, near-shore area closures lead to a smaller amount of trips but of longer duration. The crew continues to receive wages from the increased travel days, but that does not benefit the boat owners. Thus inshore area closures have a bigger impact on incomes accruing to boat owners. On the other hand, distant area closures such as turtle conservation policies lead to a larger number of lower duration trips and has the opposite effect. Fiscal policy instruments such as auction fee increases however, have a significant effect on both parties because there is limited scope for substitution, while trips yielding marginal returns are no longer profitable.

The other major impact of turtle conservation is the increased harvesting of near shore species such as yellowfin, bigeye and striped marlin. Although not considered in the model, this can adversely affect catches by competing fleets such as handliners and trollers as well as recreational vessels. However, nearshore area closures increase swordfish catches marginally but have a positive impact on the stocks of the competing species.

Our results can be used to compute the rough implicit price of saving a loggerhead turtle. For example, Kleiber (1998) estimates that 66 loggerhead turtles were killed through interaction with longline gears in 1995. Then using our model results, the rough cost of adopting turtle conserving policies in terms of foregone profits to the longline fleet is approximately $14,924 per turtle. These types of implicit valuations can be used by policy makers to analyze tradeoffs and make appropriate policy decisions.

The model developed in this paper can be improved in several different ways. The initial fish stock size is estimated based on current catch and hook data, assuming no inflow or outflow within a period but allowing for stock changes across each period, i.e., between successive months. Possible extensions include incorporating a migration function that allows for locational stock movements that are a function of stock differentials between adjacent grids. This function may display seasonal variations based on biological information on pelagic fish movements.

Possible improvements in future research include estimation of the labor supply function using several years' data. Additional factors affecting fishing effort supply (e.g., time lag, income from non-fishing activities) could also be modeled in later work. The model does not account for interactions with other gear types (e.g., handline and troll). For example, moratorium on distant shore fishing will increase inshore fishing by longline boats and may increase incidence of gear conflict. Lastly, the price and catch data used is for the most recent year (1995) available while the cost data is for 1993. This asymmetry could introduce errors in simulation although it is implausible that the cost structure may have changed significantly within two years. New cost-earnings data from recent NMFS surveys could be used to further improve the predictive power of the model.

Appendix 1

Calculation of Normalized Crew Wage

Dividing crew income by trip length will yield biased estimates of crew wages since both fishing and travel days are included in computation of trip length and trips to different locations will entail different travel times. Given the nature of activities on board, wages per fishing day are expected to be higher than wages per travel day. To obtain this relationship, 95 available observations from 1993 trip data collected by Hamilton, Curtis, and Travis (1996) was used to regress the average crew income per trip with the average numbers of fishing days and travel days per trip as

$$AW_j = 917.17 \times FD_j + 348.87 \times TD_j \tag{A1}$$

$$(9.21) \qquad\qquad (2.80)$$

where AW_j, FD_j and TD_j are the average crew income and numbers of fishing days and travel days per trip for vessel *j*, respectively. The above *t*-ratios suggest that both parameters were statistically significant at the 5% level. Although the number of fishing days per trip is fixed in our model, there was some variation on average number of fishing days in the data. The mean and standard deviation were 10.6 and 2.9, respectively. Since the Breusch-Pagan test rejected the null hypothesis of homoscedasticity, heteroscedasticity was corrected using Shazam econometric computer software (White, 1993). The intercept was negative and insignificant in the preliminary estimation, hence was restricted to zero.

The above results imply that the expected wage per travel day is 38.04% (= 348.87/917.17) of the wage from a fishing day. Therefore, we remove this bias by calculating the normalized crew wage (*NCW*) for a trip to area *k* as the crew income at location *k* divided by the "effective trip length" as follows:

$$NCW_k = \frac{CI_k}{FD + 0.3804\,TD_k}. \tag{A2}$$

Appendix 2

Estimation of the Ratio of Catchability Coefficients

From (12) define $X \equiv f\left(E_k, \gamma_i\right) = \gamma_{i1} E_{k1} + \gamma_{i2} E_{k2}$. Then the catch function (1) can be expressed as $C_{i,k} = \left(1 - e^{-X}\right) B_{i,k}$. Since X is usually between zero and unity (Deacon 1989), we can now expand $\left(1 - e^{-X}\right)$ around $X = 0$ as a Taylor series to get

$$1 - e^{X} = \frac{X}{1!} - \frac{X^2}{2!} + \frac{X^3}{3!} - \frac{X^4}{4!} + \cdots \tag{A3}$$

which yields a modified catch function

$$C_{i,k} = B_{i,k} \alpha_{i,k} X = B_{i,k} \alpha_{i,k} \left(\gamma_{i1} E_{k1} + \gamma_{i2} E_{k2}\right) \tag{A4}$$

in which

$$\alpha(X) = 1 - \frac{X}{2!} + \frac{X^2}{3!} - \frac{X^3}{4!} + \cdots . \tag{A5}$$

where α is positive and monotonically decreasing with X from a maximum value of unity. (A5) implies that catch-per-unit-effort (CPUE) declines with increased effort due to the stock externality. Catches from tuna ($C_{i,k1}$) and swordfish sets ($C_{i,k2}$) in area *k* can be separated from (A4) as

$$C_{i,k1} = B_{i,k} \alpha_{i,k} \gamma_{i1} E_{k1} \tag{A6}$$

$$C_{i,k2} = B_{i,k} \alpha_{i,k} \gamma_{i2} E_{k2}, \tag{A7}$$

where $C_{i,k1} + C_{i,k2} = C_{i,k}$. Dividing (A7) by (A6), we obtain

$$\frac{\gamma_{i2}}{\gamma_{i1}} = \frac{CPUE_{i,k2}}{CPUE_{i,k1}} \tag{A8}$$

where $CPUE_{i,k1} = C_{i,k1} / E_{i,k1}$ is CPUE for species *i* in area *k* for the tuna set (similarly for the swordfish set). In (A8), both catchability coefficients (γ_{i1} and γ_{i2}) are assumed constant, while CPUE is expected to fluctuate over seasons and vary across fishing locations. We can now estimate the catchability ratio ($\gamma_{i2} / \gamma_{i1}$) from the CPUE ratio in (A8). Since the noise associated with CPUE data is expected to be large due to fluctuations in stock size within each month and non-uniformity of fish stocks within each location (five-by-five degree square), we only use data points that consist of at least 30 sets each of the tuna and swordfish sets. The resulting estimates of the catchability ratio for the five species are presented in Table 1. Okamoto (1999) computed the average CPUE ratios by swordfish and tuna sets and obtained similar results.

Iterative Procedure of OLS Estimation for Catchability Coefficients

Suppose only one type of fishing strategy is used to catch a single species, then given the catch function (A4), a series of harvests in a fishing location over consecutive periods yields the following sequence of catches:

$$C_1 = \gamma\, \alpha_1\, E_1\, B_1$$
$$\vdots \qquad \vdots$$
$$C_t = \gamma\, \alpha_t\, E_t\, B_t \tag{A9}$$
$$C_{t+1} = \gamma\, \alpha_{t+1}\, E_{t+1}\, B_{t+1} = \gamma\, \alpha_{t+1}\, E_{t+1}\left(B_t - C_t + R_t\right)$$

where all subscripts denote the time period, and subscripts denoting species, area, and fishing strategy are omitted for notational simplicity. The net stock inflow during period t, R_t, is defined as the total fish stock inflow minus the stock outflow and natural mortality. It is positive if the inflow is greater than the outflow, and vice versa. Note that in (A9), the fish stock changes between periods due to harvest and in and out-migration of fish. Expressing the previous equations in terms of $CPUE_t/\alpha_t$ and subtracting the equation for t from $(t+1)$, we get

$$\frac{CPUE_{t+1}}{\alpha_{t+1}} - \frac{CPUE_t}{\alpha_t} = \gamma\left(-C_t + R_t\right) \tag{A10}$$

where $CPUE_t = C_t / E_t$ is catch-per-unit-effort at period t. To econometrically estimate γ, we assume that the Hawaii pelagic fishery is in long-run equilibrium; i.e., the expected net inflow is equal to the expected catch per period in each area. Then rewriting (A11) as

$$\frac{CPUE_{t+1}}{\alpha_{t+1}} - \frac{CPUE_t}{\alpha_t} = -\gamma\left(C_t - \overline{C}\right) + \varepsilon_t \tag{A11}$$

where $\overline{C}$ is the average catch per period, $R_t = \overline{C} + \frac{\varepsilon_t}{\gamma}$ and $E(\varepsilon_t) = 0$. (A11) implies that a change in CPUE adjusted by α (denoted by $\Delta CPUE_{adj}$) between consecutive periods is a negative linear function of catch in the current period. The long-run equilibrium assumption is supported by Boggs and Ito (1993) and other studies of the Hawaii pelagic fishery, who report that species abundance estimated by measures such as average CPUE and average weight per fish has not changed to any significant degree (WPRFMC, 1997).

The estimated parameter γ in (A11) affects the dependent variable since α_t is a function of γ and effort level E as in (A5). Therefore, we use an iterative procedure to estimate γ in (A11); i.e., (i) first estimate or guess γ, (ii) compute α_t and $\Delta CPUE_{adj}$ for all observations with this tentative γ, (iii) perform another round of estimation with (A11) to get the new γ, and (iv) repeat the estimation procedure until the estimate of γ converges.

A panel data set with monthly catch and fishing effort data aggregated for each five degree square was used. Data from "swordfish-set-dominant" areas was used to estimate the catchability coefficient for swordfish with a swordfish set (γ_{i2}), while data from "tuna-set-dominant" areas

was used to estimate the catchability coefficients for the other four species with a tuna set (γ_{i1}). Results from the final iteration of the OLS procedure are shown in Table 10. All estimated catchability coefficients were significant at the 1% level with expected signs. The R^2 scores were relatively low, and ranged from 0.1761 to 0.3716. It is to be expected because exogenous seasonal (i.e., monthly) fluctuations in the net inflow are accounted for by the error terms in the model, and pelagic fish abundance in Hawaii is likely to be most strongly affected by factors other than local fishing activity (Boggs and Ito, 1993). The R^2 scores for the three most valuable species (bigeye and yellowfin tunas and swordfish) were higher than those for albacore and striped marlin, which might reflect the relatively greater influence of fishing effort on $\Delta CPUE_{adj}$. Although the cross-sectional time-series data was pooled, neither autocorrelation nor heteroscedasticity was detected.

TABLE 10
Results of the Interactive Estimation Procedure for Catchability Coefficients, by Species

Species (i)	Set Type (s)	Catchability Coefficient ($\gamma_{i,s}$)	R^2	Number of Observations
Swordfish	Swordfish set	0.00483 (4.46)	0.3273	35
Bigeye Tuna	Tuna set	0.00338 (5.63)	0.3716	55
Yellowfin Tuna	Tuna set	0.00378 (4.94)	0.3172	55
Albacore Tuna	Tuna set	0.00431 (3.45)	0.2063	55
Striped Marlin	Tuna set	0.00248 (3.24)	0.1761	55

Note: Numbers inside the parentheses are t-ratios, which indicate statistical significance at the 0.01 level.

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