Regulatory Impact Analysis for Pelagic Fishery Management in Hawaii: A Spatially Disaggregated Nonlinear Programming Model

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ABSTRACT

A major challenge confronting pelagic fisheries management in Hawaii is to simultaneously achieve two different and possibly conflicting objectives: conserving protected species (sea turtles and sea birds) while maintaining a viable fishery. To illustrate the difficulty of achieving these objectives, recent regulatory policy—the prohibition of all shallow longline sets (that primarily target swordfish at depths less than 100 m), combined with a spatial and seasonal closure south of 15°N during April–May—substantially reduced incidental sea turtle takes, but probably contributed to a sharp decline of the ex-vessel revenue (from $50 million in 2000 to $33 million in 2001) accruing to the Hawaii-based longline fishery (HILLF).

We have developed a nonlinear programming model to evaluate the impacts of existing and possible alternative policies on the HILLF. We did this by incorporating (i) recent data from stock assessment and ecological studies for pelagic species in the Pacific Ocean, and (ii) detailed economic factors, including ex-vessel fish prices, operational costs, labor costs, annual fixed costs involved in longline operations, and entry conditions for vessel owners, crews, and fishing trips. A specialized data management methodology was developed to support a flexible area, season, target, and species classification system for the model.

The baseline case, in which the HILLF was assumed to be in an open access situation (i.e., where the fishing trips are allocated until the economic rent is dissipated) without any major regulatory actions, over-allocated longline sets by 27% in 1993 and 15% in 1998 compared to the actual data. This probably occurred because the model took no account of imperfect competition or inefficient allocation of fishing effort due to uncertainty in fish abundances and prices. However, the revenue per set, as a crude measure of productivity, suggests that the model predictions were similar to the actual. Although there was little change in the total number of sets from 1993 to 1998, the primary target shifted toward bigeye tuna (from 39% in 1993 to 63% in 1998). Because a tuna set (targeting bigeye tuna), in general, yielded less revenue with lower operating costs (despite its use of greater number of hooks deployed) compared to a swordfish set, this shift in the primary target resulted in a considerable decrease (13%) in the fleet-wide revenue from 1993 to 1998. The model predictions captured those changes.

Moreover, the model overall accurately predicted the changes due to the recent management regulations for sea turtle conservation in terms of productivity and effort distribution by target and area. However, the actual total number of fishing sets was much more than the model predicted; in fact, it increased despite the aforementioned revenue loss caused by the tight regulations. Possible reasons include (i) the employment of foreign crew to reduce costs involved in longline operations, and (ii) considerable variation in CPUE and RPUE of major species as well as their market prices and weights.

The model demonstrated its usefulness in analyzing the impacts of various regulatory policy options for the HILLF, such as time/area closures. Improvement in the accuracy of the model predictions depends on the availability of updated information from stock assessment and socio-economic studies.

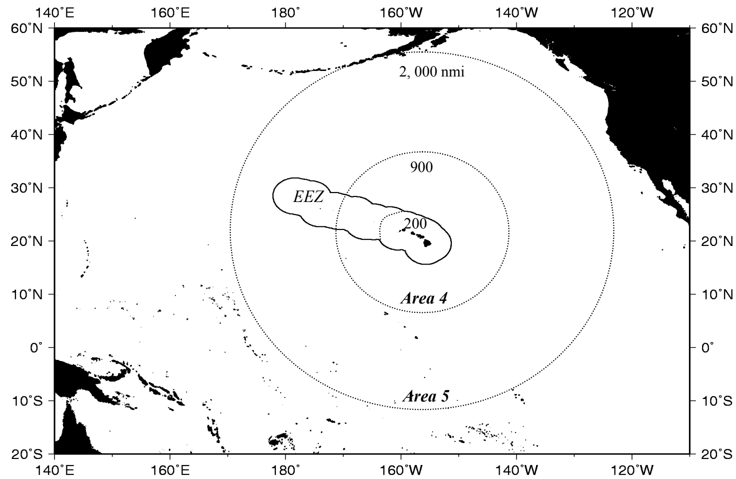
INTRODUCTION

Fishery management has failed to prevent the collapse of many fishery resources (Hennessey and Healey, 2000; Jakobsson and Stefansson, 1998), and as a result there is concern for the management of highly migratory pelagic species. Until now there were no models which could sufficiently assist in the management of pelagic species. Even though research results from some models are available, none have proven sufficient to guide development of effective policies (Schnute and Richards, 2001). This reflects the complex nature of pelagic fisheries management: in particular, research results would not be empirically useful unless a model could incorporate both up-to-date information on the behavior of fishing fleet and population dynamics of multiple species, with the variability associated with each.

The Hawaii pelagic fishery is such a complex fishery system, in which the Hawaii-based longline fishery (HILLF) is the largest component. This fishery catches two major target species, bigeye tuna (*Thunnus obesus,* BET) and swordfish (*Xiphias gladius*, SWF), and many valuable non-target species. Incidental catch of protected species—particularly sea turtles and sea birds—has been a crucial issue for fishery management. Various regulatory policies, including time/area closures, to protect sea turtles were evaluated and implemented (NMFS, 2001). For example, a simulation model developed by Kobayashi and Polovina (2001a) in response to a judicial order (NMFS, 2001), was designed to identify a range of effective regulations to protect sea turtles, and a regulatory policy recommended by this model was implemented on March 30, 2001 (Kobayashi and Polovina, 2001b).

The Kobayashi and Polovina (K-P) model has some limitations as a forecast model because (i) its assumptions concerning the behavior of the longline fleet are not grounded in economic theory, and (ii) the actual experience in the fishery contrasts with the K-P model predictions. Specifically, although the total number of fishing sets was assumed to remain at the same level or decline after a turtle conservation policy was imposed, the number of sets actually increased during 2000-2002 by 5% on average even as the number of hooks increased significantly (by 33%).

Although a few economic models were developed to analyze the HILLF, these models had some limitations, in particular, regarding area designations. While the range of various recent policy options for time/area closures differs by as little as 1° square, (i) the resolution of a grid of 5° squares used in Chakravorty and Nemoto (2001) was not sufficient, and (ii) the five concentric areas based on distance from the Honolulu port in Pan et al. (2001; see Figure 1) were not suitable. Although neither model was readily adjustable to flexible area designations, it was empirically easy to enhance the Pan et al. (2001) model because many assumptions in the Chakravorty and Nemoto model (2001) depend heavily on its area designation.



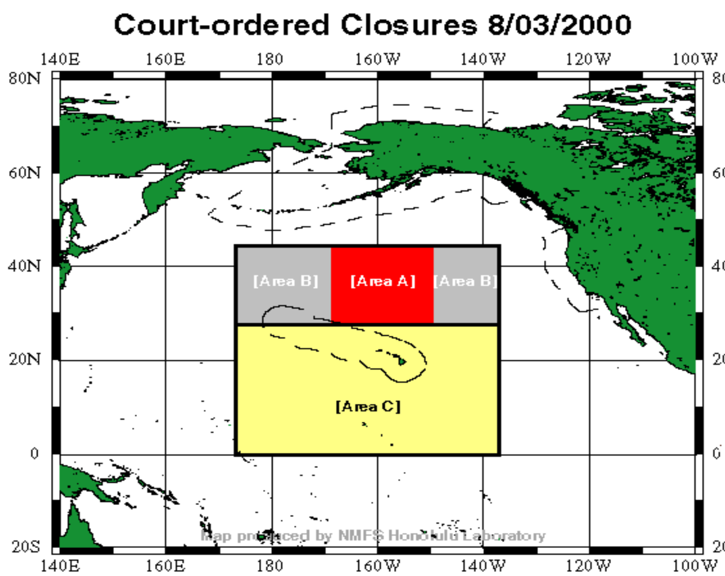


Figure 1. Changes in preferable area definitions for policy simulations: the upper figure represents the area designation in Pan et al. (2001), and the lower figure represents one of court-ordered area closures in 2000:

Area A: 44°N–28°N and 150°W–168°W
Area B: 44°N–28°N, and 137°W–150°W or 168°W–173°E
Area C: 28° N–Equator. and 137° W–173° E

The need for appropriate policies that balance the various objectives has been underscored by several developments regarding the HILLF. First, the Hawaii Longline Association (HLA) filed on April 10, 2001, for declaratory and injunctive relief from the area closure implemented by the NMFS. Second, the current policy resulted in a significant increase of fishing pressure on BET (Fig. 2). Third, the overall effectiveness of the turtle conservation policy transferred the opportunity to target and catch swordfish to non-Hawaii fleets which may take more sea turtles than the HILLF (Kaneko and Bartram, 2003). Thus, an effective and efficient economic model is needed to evaluate the impacts of the various regulatory policies, in particular, time/area closures with resolution of 1° square.

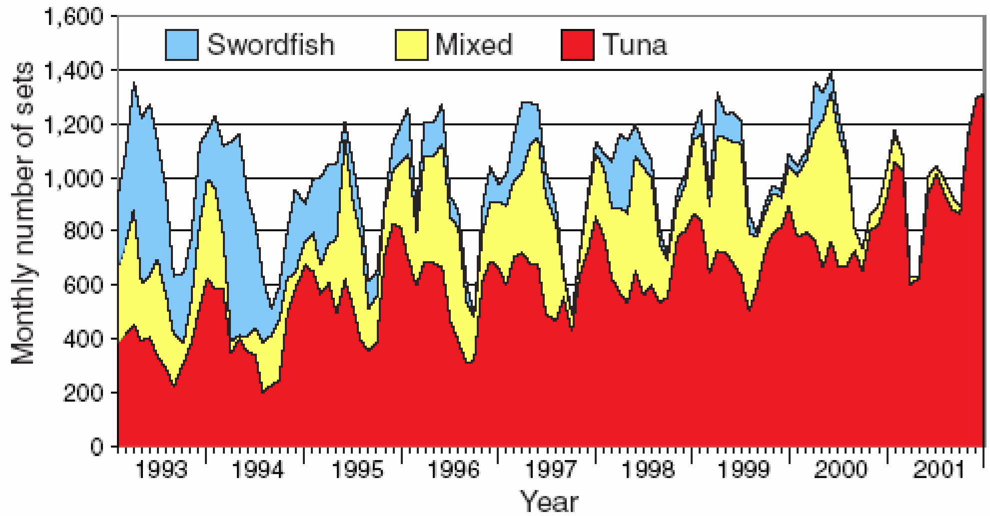


Figure 2. Monthly number of fishing sets by target, 1993-2002

OBJECTIVE

The objective of this study is to enhance a multilevel and multi-objective programming model (MMPM1, developed by Pan et al. 2001) suitable for evaluating regulatory policies on pelagic fisheries in Hawaii. The model revisions include (i) improving the model, by using an alternative catch function employed commonly in stock assessment and ecological studies (e.g., Boggs et al., 2000; Cox et al., 2002a and 200b; Hampton et al., 2003), and (ii) developing data management system to support flexible time and area designation.

RECENT REGULATIONS TO PROTECT SEA TURTLES IN HAWAII

The HILLF is the largest commercial fishery in Hawaii, generating about $42-$50 million during the last decade (Ito and Machado, 2001). The interaction of four species of sea turtles—loggerhead, leatherback, olive ridley, and green turtles—with longline gear has been a major concern in the Hawaii pelagic fishery management. Annual mortality of loggerhead turtle ranged 64-88 for 1994-1999, which was the greatest among the four species (McCracken, 2000).

Two policies for sea turtle conservation were subsequently implemented:

Policy 1: Closing a zone north of 28°N latitude and between 150°W and 168°W longitude during December 1999–March 2001, Policy 2: Prohibiting all "shallow sets", which are primarily associated with the targeting of swordfish. A spatial and seasonal closure south of 15°N during April-May was also implemented for all remaining longlining, in particular deep sets (targeting BET). This policy was in effect April 2001–March 2004.

Policy 1, created by judicial order, continued until the National Marine Fisheries Service (NMFS) completed an environmental impact statement (EIS) on the turtle issue (NMFS, 2001). Closely following the recommendation in the final EIS, the regulations were modified to prohibit all "shallow" sets, which usually target SWF, because these had taken more turtles than "deep sets" targeting BET. According to the federal judge's ruling, the minimum depth of longlines would be set to 328 feet, while the standard depth of a swordfish set ranges from 70 to 100 feet. Furthermore, a zone south of 15°N was closed during April-May to minimize interactions with leatherback and olive ridley turtles, thought to migrate through that area at that time of year.

THE MODEL

Appendix 1 presents the equations for this mathematical programming model (MMPM2), which were modified from MMPM1 (Pan et al., 2001) in two major aspects. First, an alternative objective function, maximizing total revenue, was substituted for the previous one (maximizing economic rent) because the HILLF is believed to more closely resemble an open access situation than a monopoly or economic rent maximization situation. Moreover, the number of longline vessels with permits is 164, but the active number of vessels each year ranged between 103 and 125 since 1993 (Ito and Machado, 2001). It means that the number of active vessels in the HILLF was likely to be determined endogenously. In other words, the HILLF industry had been quite competitive with more than 100 vessels, in which the economic rent would be dissipated (i.e., the profits generated from each vessel were zero). Therefore, the actual total output of the industry is expected to be much greater than the output level of the rent-maximization model, and to be close to the output level of an open access scenario (Figure 3).[1]

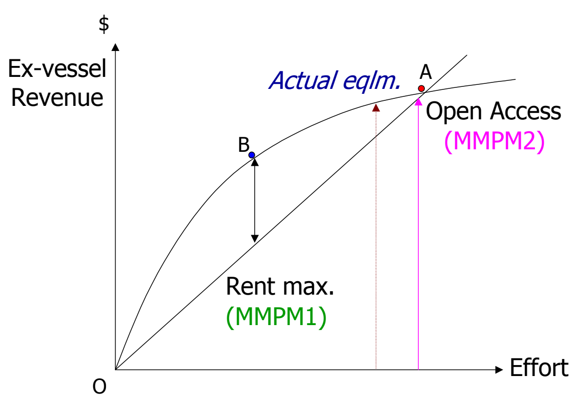


Figure 3. Comparison of rent maximization, open access, and actual equilibrium point.

Second, a new catch-per-unit-effort (CPUE) profile with declining catch rates was substituted for the previous one in Pan et al. (2001), which incorporated a declining catch rate (DCR1) but was neither empirically grounded nor consistent with biological assumptions for fish stocks. An alternative CPUE function, where CPUE declines with fishing pressure in the

[1] The actual total output of the HILLF is expected to be slightly less than the "optimal" level in an open access situation, because fishers, in reality, could not optimally allocate their trips.

short run, was derived from a catch function that is widely used in stock assessment studies (Fournier, Hampton, and Sibert, 1998; Boggs et al. 2000; Hampton et al., 2003) and ecological models (Cox et al., 2002a,b). An economic model must usefully adopt an appropriate catch function because the estimated fish stocks or CPUE are essential inputs for any economic and management decisions. Such information is usually available from other studies related to stock assessment, rather than economic studies. Moreover, the efficacy of the model is most likely to be evaluated by biologically trained managers. A catch function should serve as a link to other interdisciplinary research to contribute to ecosystem-based fishery management.

The alternative catch function, ignoring fleet (vessel size) i and target (set type) j, is

$$C_{skt} = \frac{F_{skt}}{Z_{skt}}\left(1-e^{-Z_{skt}}\right)X_{skt} \qquad (1)$$

where

C_{skt} is the average catch per month of species s at area k during period t in terms of number of fish,

$Z_{skt} = M_s + F_{skt}$ is the instantaneous total mortality rate, (2a)

$F_{skt} = q_s E_{kt}$ is the instantaneous fishery mortality rate, (2b)

M_s is the instantaneous natural mortality rate (constant),

E_{kt} is standardized fishing effort per month at area k during period t,

q_s is catchability coefficient for species s (constant), and

X_{skt} is the fish stock, measured as the average number of species s (with appropriate age/size as a target of longline set) per month within period t in area k in the absence of fishing mortality at all. Note that X_{skt} is a parameter (given) in the model, although it must be estimated (explained later).

For convenience for explanation, we also define

$TM_{skt} = \left(1-e^{-Z_{skt}}\right)$ as the total mortality rate. (3)

Although fishery economists often ignore natural mortality (Deacon, 1989; Chakravorty and Nemoto, 2001), this study includes natural mortality M in Eq. 2a to permit comparison with other stock assessment studies.

By transforming the above catch function (1) (see Appendix 2 for derivation), the following CPUE profile function is obtained:

$$CPUE_{skt} = CPUE^0_{skt} \cdot \alpha_{skt} \qquad (4)$$

where

$$\alpha_{skt} = \begin{cases} \left(\dfrac{1-e^{-Z_{skt}}}{Z_{skt}}\right) & if\ Z_{skt} > 0 \\ 1 & if\ Z_{skt} = 0. \end{cases}$$

The coefficient α, which decreases from 1 and approaches towards zero as Z_{skt} increases, measures the decline of CPUE due to fishery catch in the short run. Hence the coefficient α can be defined as the "coefficient of stock externality". Here, Z_{skt} for species s is a function of E_{kt} since M_s and q_s in Eqs. 2a and 2b are constant, and then $CPUE$ monotonically declines from $CPUE^0$ as E_{kt} increases due to stock externality (which is sometimes referred as "fish down", "short-term depletion", or the response of fish stock to fishing pressure") as illustrated in Fig. 4. Moreover, the greater q_s implies more sharp decrease in CPUE due to stock externality. On the other hand, $CPUE^0$ represents natural abundance only, which theoretically excludes the effect of fishery catch, and hence can be used as a relative abundance index. Moreover, the form of Eq. (4) (hereafter denoted as Declining Catch Rate version 2, DCR2) may be more useful than the original catch function, Eq. (1), because CPUE is more commonly used and more independent of the definition of area and period while the stock, and other variables/parameters in the catch function (1) depend on the size of an area or the length of a period.

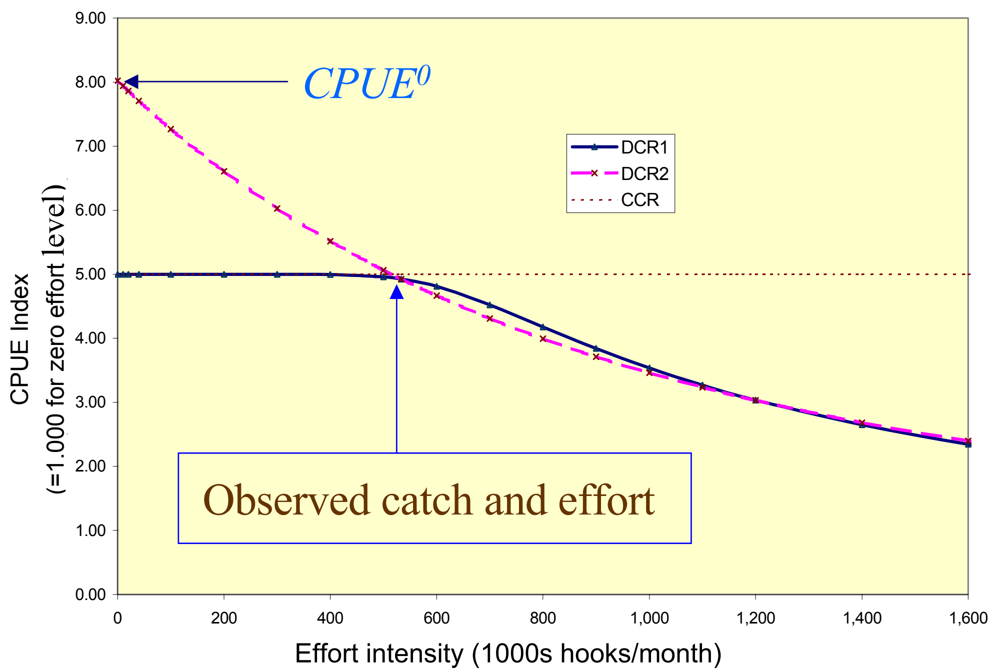


Figure 4. CPUE profile used in this study (DCR2) compared to those used in the previous study (Pan et al., 2001) (i.e., CCR and DCR1).

While the initial stock X_{skt} was previously assumed to be 150% of the actual catch at all areas at all periods (i.e., $TM_{skt} \equiv 66.7\%$; see Leung et al. (1999), p. 52), TM_{skt} depends on fishing effort in this model (DCR2: see Eq. 3). In addition, the "Constant Catch Rate (CCR)" model in Pan et al. (2001) can be considered a special case of DCR2, in which $q_s = 0$ in Eq. 2b, and hence α in Eq. 4 would be constant for any effort level E_{kt}. Thus, DCR2 supersedes DCR1 (see Appendix 3 for the comparison of DCR1 vs. DCR2).

AN APPLICATION TO THE HAWAII-BASED LONGLINE FISHERY (HILLF)

This section first defines fishing areas and periods, designed to evaluate the impacts of the aforementioned regulations on the HILLF. Next, the data processors that generate updated parameters from several databases (i.e., logbook, auction data, cost-earnings survey data) are explained. Third, fish prices are analyzed by regressions and the predicted prices of each species are used as a proxy for the fishers' expected price.

Fishing grounds for the HILLF are divided into the following five areas (Figure 5) based on empirical observation of fleet operating patterns (time-area decisions) and regulations.:

K1: Main Hawaiian islands (MHI), 5° square,
K2: Northeast (NE): north of 15° N and east of 158° W, excluding MHI and NC,
K3: North central (NC): 28°–44° N and 145°–168° W,
K4: Northwest (NW): north of 15° N and west of 158° W, excluding MHI and NC,
K5: South of 15° N.

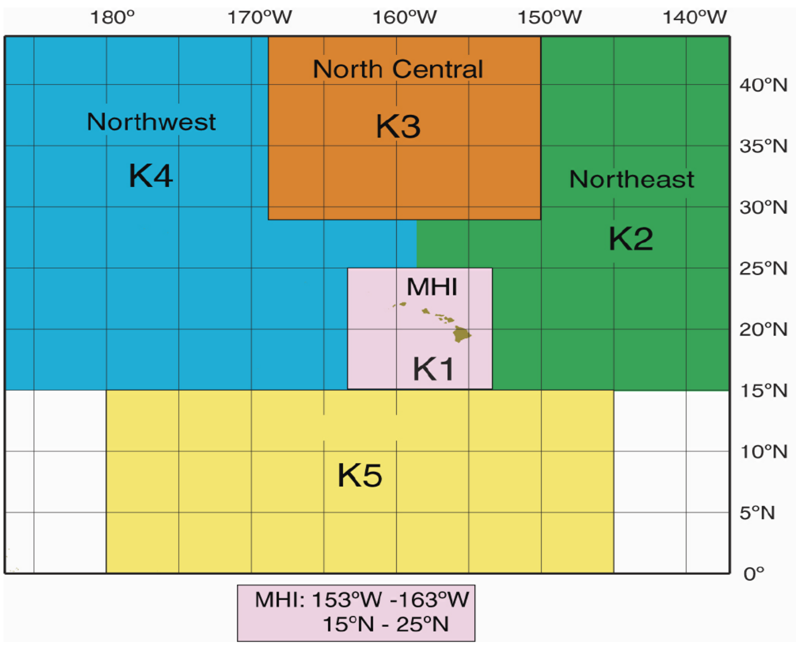


Figure 5. Five areas analyzed for the impacts of turtle conservation policies.

Area K1, MHI area (near shore), which covers a square of about 5° north, south, east and west of Honolulu (15°–25° N and 153°–163° W), is defined as an independent area because the traveling cost to this area is the lowest; 40–60% of all longline sets were actually deployed in this rectangle every period. Areas K3 and K5 need to be independent areas so that we can simulate time/area closures. While area K3 ("North Central", NC) was closed during December 1999–March 2001 (Figure 1), area K5, south of 15° N above the equator, has also been closed during April–May since 2001. The rest of Hawaiian waters north of 15° N are divided into two areas—"Northeast (NE)" and "Northwest (NW)"—by 158°W longitude. Longline trips targeting SWF were the predominant activity in both areas until March 2001.

Figure 6 shows the annual numbers of fishing sets by area during 1993-2001, indicating that one third to one half of the total sets were allocated to the MHI area (K1). The regulatory policy during 2000 (Policy 1, closing K3) did not reduce the total number of sets. Rather, effort formerly allocated to area K3 moved to the NE and NW areas. However, Policy 2 (since April 2001) reduced the fishing sets in the three northern areas (K2, K3, and K4) because it prohibited all shallow sets (both swordfish and mixed types of sets), while it also reduced sets in the south (K5) due to its closure during Apr-May. It resulted in many of those reduced sets being reallocated to the MHI area, although the total number of sets fishing sets slightly decreased.

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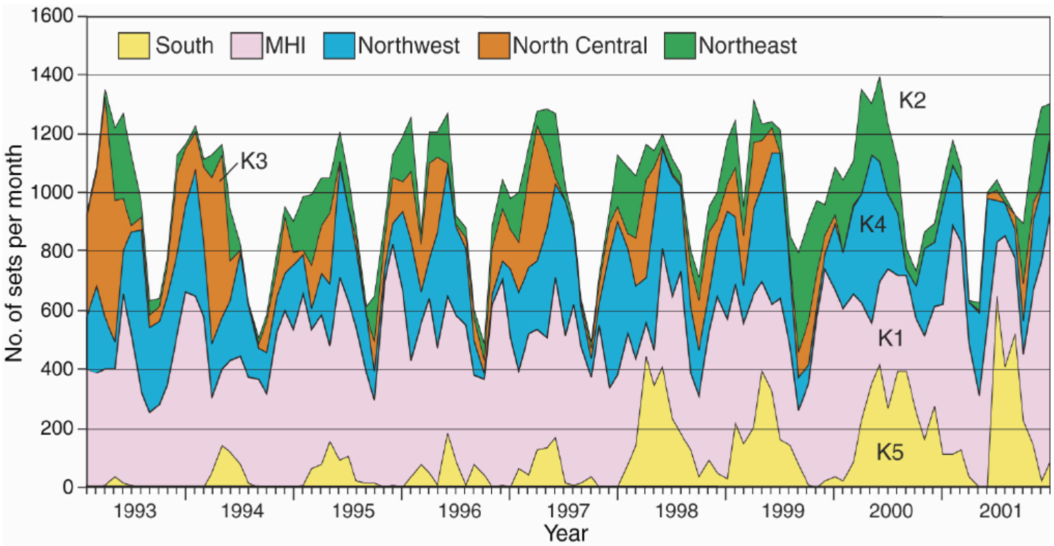

Figure 6. Number of fishing sets, by area, 1993-2001.

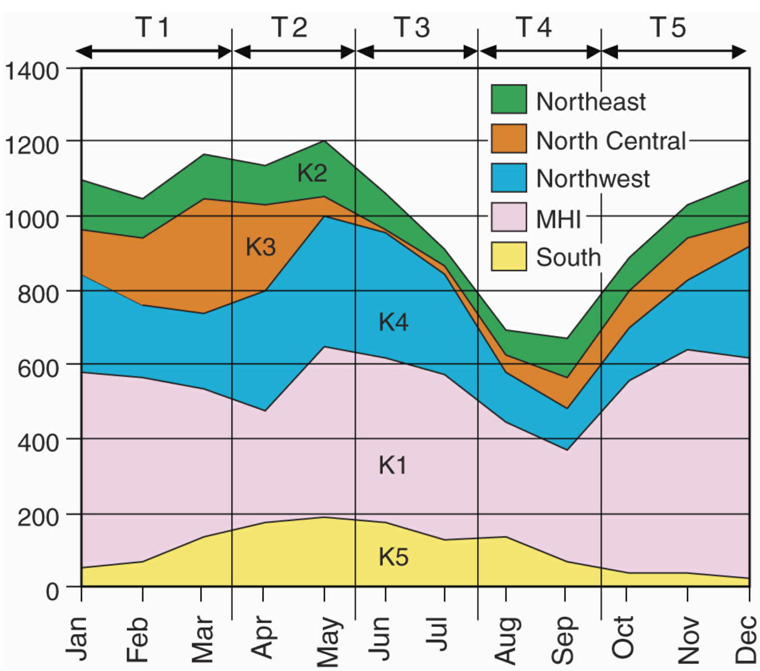

Figure 7. Fishing sets by area and month, for five defined periods (T1-T5).

Definition of period (or season) and fishing intensity

Previous studies (Chakravorty and Nemoto, 2001; Pan et al., 2001) suggested that the seasonal variation in fish price/weight and abundance (CPUE) affected effort allocation by the HILLF. The average numbers of fishing sets by area and month during 1993–2001 are presented in Figure 7), showing that the number of fishing sets sharply declined from the peak in May to the bottom in Aug–Sept. This figure indicates the significance of seasonal changes in fish prices and/or abundance.

It must be noted, however, that a period may need to be defined to correspond to the duration of any time/area closure, which could be 1, 2, or any months. This implies that the length of a period must be flexible (not constant) to be able to simulate the seasonal closures. On the other hand, "stock externality" (i.e., short-term depletion of the stock) should be a function of fishing intensity, to be measured by the effort level over an equal time period. Therefore, effort, catch, stock and other variables are measured as monthly averages, while the length of each period might vary.

Specific to this application, because the South area has been closed during April–May since 2001, these two months need to form a period to simulate this time/area closure. Since it is more practical to avoid a period over two consecutive years, the first quarter should reasonably form the first period in each year. The rest of a year, seven months from June-December, is divided into 3 periods—rather than two periods—because a period of 4 months or longer is probably too long to capture seasonal fluctuations in fish abundance and price. Historically the average number of sets deployed during August-September is less than other months (Figure 7), suggesting that these two months also form a distinct period. Thus, one year is divided into the five periods (or seasons) as shown in Table 1.

Table 1. Definition of periods (seasons), effort, and fishing intensity at MHI area in 1993.

	T1	T2	T3	T4	T5
	Jan-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Dec
Length of season (month)	3	2	2	2	3
Effort (E_{kt})*	1,483	1,226	1,055	664	2,048
Fishing intensity (E_{kt} / month)	494	613	527	332	683

*1 unit effort = 1,000 hooks

Since this model incorporates a decline of CPUE in the short run (i.e. within a period) caused by fishing pressure, the fishing intensity is measured as monthly effort (i.e., avoiding variable length of period). For example, as illustrated in Table 1, more hooks were deployed in the MHI area during T1 (Jan-Mar, 3 months) than T2 (Apr-May, 2 months). However, the fishery was more intensive during T2 than T1 because the length of T2 (2 months) is shorter than T1 (3 months), and the fishing intensity (average monthly effort) during T2 was greater than during T1. In another comparison, the fishing intensity during T3 was 527 and almost the same level as during T1 (494), despite the total number of hooks deployed during T3 (1,055 thousand hooks) was less than during T1 (1,483 thousand hooks).

Data Processing

Three data sources were utilized in this study: (i) longline logbook data, (ii) auction data, and (iii) cost-earning survey data (Figure 8). Catches by species and operational information (e.g., numbers of sets, hooks and light-sticks) summarized by 1°×1° square, month, fleet (small, medium, or large longline vessels), and target (tuna/mixed/swordfish) are available in the National Marine Fisheries Service (NMFS) Honolulu Laboratory logbook archive. Then the above data sets were stratified into the areas and periods defined above, using SQL (structural query language) provided by a database software package (FoxPro for Windows version 2.6a). Areas and periods can be altered with simple modifications of SQL parameters with respect to positions (latitude/longitude) and months. Observed effort (as thousands of hooks) and catch of each species in each stratum (each area and period) were used to estimate the initial stock X and $CPUE^0$, which are used as parameters for MMPM2. Auction data, collected by NMFS employees, were used to compute the average price ($/lb) and weight (lb/fish) during each period. The cost-earning survey data (Hamilton et al. 1996) were used to estimate (a) fixed costs (annual) for each vessel and (b) expected wage ($/vessel-day) by fleet type (Large/Medium/Small), and (b) operating costs for fishing and traveling days ($/FD & $/TD) by size and target.

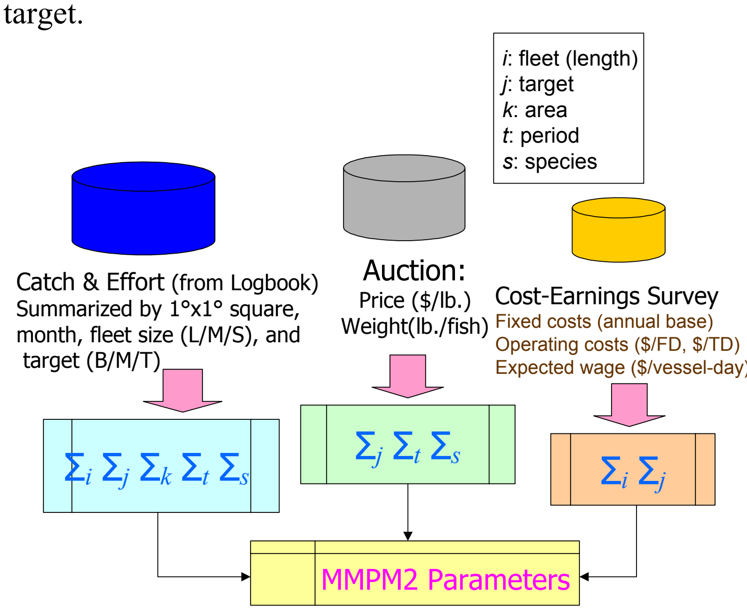

Figure 8. Flow chart for data processing**.**

Estimation of catchability coefficients for species s (q_s)

Longline sets in Hawaii were categorized as (1) "tuna" set, (2) "swordfish" set, and (3) "mixed" set before the 2001 regulations. A typical tuna set—which is set deep in the water during daytime with “sanma” (saury, *Cololabis saira*) as bait—targets bigeye tuna (BET), whereas a swordfish set is set shallow in the water and soaked overnight using more expensive bait (squid) and lightsticks to target swordfish (SWF). Although the definition of “mixed” set is unclear (see Hamilton et al. 1996), it could include all sets that cannot be categorized as either tuna or swordfish sets. Most mixed sets are soaked shallower than a tuna set, but also use fewer (if any) lightsticks compared to a swordfish set. Among these three set types, a swordfish set catches 1.04 times more SWF than a mixed set, and 34.55 times more SWF than a tuna set. Therefore, the nominal amounts of effort (1,000 hooks) by mixed and tuna sets are divided by 1.04 and 34.55, respectively, to standardize effort for SWF catch[2]. Likewise, nominal effort is standardized with respect to other species, too, although differences across the three types of sets are much less than SWF.

Catchability coefficient q_s is an important parameter (constant) measuring a decline of CPUE due to stock externality. This study assumes q_s (constant) for species s by focusing on the total mortality rate TM. Equations (1-5) indicate that (i) the total mortality rate TM, meaning the percentage of the fish removed by fishery or natural/predatory death during a period is determined by Z, (ii) Z consists of instantaneous rate of natural mortality M (including killed by predators) and fishing mortality F (caught by fishing boats), and (iii) $F_{skt} = q_s E_{kt}$. It means that q_s would be obtained if TM is known (or assumed). Given fishing intensity level, the greater q_s implies more decline in CPUE due to stock externality, compare to the hypothetical situation with no effort allocated.

Despite several studies trying to estimate TM or instantaneous fishery mortality F, the true value of TM, which represents fishing pressure, for the North Pacific is still uncertain. More sophisticated methods with more complete data sets may be required for further accurate estimates for TM of the major species in the North Pacific. More importantly, fishing pressure actually varies across areas and periods, the “average” over broad areas, particularly if including those that were unfished in certain periods, could be misleading (Walters, 2003).

Therefore, we focus a stratum (a specific area and period), in which fishing effort is at maximum, instead of the average TM value over all areas and periods. This method was used for two reasons. First, estimates of q_s, CPUE, etc., will be more accurate if designated area and period are more specific as long as there are sufficient observations in that stratum. In general, the number of observations is sufficient at the stratum with the maximum effort level. Second, a possible range for the maximum of TM is narrower than that for the average since it should be greater than the average (if any estimates from other studies are available) and less than 100%. Besides, we could reasonably assume that the TM is unlikely to exceed 90% because of a decline in CPUE due to stock externality (Figure 9). That is, it’s not efficient to fish in such a place and time.[3] Furthermore, gear congestion, competition, and interference might contribute to additional inefficiency in fishing (Gillis, 2003; Hamilton et al., 1996) if the fishery is so intensive.

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[2] This analysis was done using the 1993 data. See Nemoto (2002) for the details about the procedure.
[3] Fishers’ decision for whether or not to go fishing also depends on fish prices (P) and stock sizes (X).

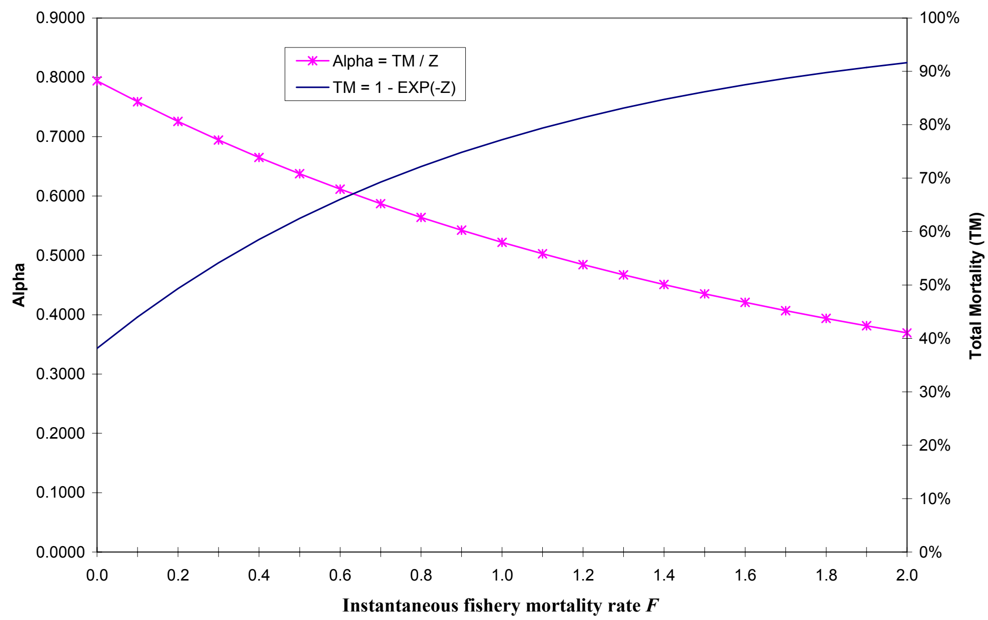


Figure 9. The relationship between α, TM, and *F*.

We first identify the period and area, in which a fishery is most intensive (i.e., the standardized effort per month in area k is greatest), and denote them as t = T* and k = K*. Then we assume that the total mortality in area K* at period T* is TM_{max}, which is likely to range from 0.70 to 0.90 for the major target species (i.e., BET and SWF). By assuming TM_{max}, the catchability coefficients for these two species are estimated as

$$\hat{q}_s = \frac{F_{s,Max}}{E^A_{Max}} = \frac{Z_{s,Max} - M_s}{E^A_{Max}} \tag{5}$$

where

$$Z_{s,Max} = \ln\left(\frac{1}{1-TM_{s,Max}}\right)$$

$$E^A_{Max} = E^A_{K*,T*} = \max_{k,t}\left(E^A_{k,t}\right).$$

Actual efforts standardized for both BET and SWF at each area and period are summarized in Table 2. The maximum fishing effort per month for BET was 683 (1 unit effort = 1,000 hooks) allocated in MHI area at period T5, while the maximum fishing effort per month, which was standardized for SWF, was 425 allocated in North Central area at T1, 1993.

Table 2. Summary of effort (1000s of hooks) standardized for tuna and swordfish sets, by area and period in 1993.

Tuna effort (standardized effort in terms of targeting bigeye tuna)

	T1	T2	T3	T4	T5	Subtotal
MHI	1,483	1,226	1,055	664	2,048	6,475
Northeast	55	492	271	86	133	1,038
North Central	1,278	577	48	73	480	2,456
Northwest	657	216	788	493	773	2,926
South	30	85	16	2	0	132
Subtotal	3,503	2,594	2,178	1,318	3,434	13,026

Tuna Intensity ("tuna effort" per month)

	T1	T2	T3	T4	T5	Monthly Ave.	Max
MHI	494	613	527	332	**683**	539.6	**683**
Northeast	18	246	136	43	44	86.5	246
North Central	426	288	24	37	160	204.6	426
Northwest	219	108	394	246	258	243.8	394
South	10	42	8	1	0	11.0	42
					Overall*	268.6	683

Swordfish effort (standardized effort in terms of targeting swordfish)

	T1	T2	T3	T4	T5	Subtotal
MHI	196	290	279	73	197	1,035
Northeast	21	439	227	38	25	750
North Central	1,276	572	48	71	470	2,437
Northwest	380	187	747	473	743	2,530
South	1	2	0	0	0	4
Subtotal	1,874	1,491	1,302	655	1,435	6,756

Swordfish Intensity ("swordfish effort" per month)

	T1	T2	T3	T4	T5	Monthly Ave.	Max
MHI	65	145	140	36	66	86.3	145
Northeast	7	219	114	19	8	62.5	219
North Central	**425**	286	24	36	157	203.1	**425**
Northwest	127	94	**374**	236	248	210.8	374
South	0	1	0	0	0	0.3	1
					Overall*	140.7	425

*South area was excluded to calculate the average since very few sets were deployed.

Next, we assume instantaneous natural mortality for BET and SWF: $M_{BET} = 0.48$, following (Hampton et al., 2003), and $M_{SWF} = 0.32$ based on Kleiber and Yokawa (2002), although while the estimate for M_{BET} by other studies is within a range of $0.4 < M_{BET} < 0.8$ (See Table

3),[4] and much less information is available for M_{SWF}. Finally, we assume the TM_{max} values to be 75% and 80% for tuna and swordfish sets, respectively, for the baseline case (see Table 4 (a,b) for details).[5] Then, catchability coefficients q_s (constant) for each set types were obtained using equation (5): q_{BET} = 0.001328, and q_{SWF} = 0.003031[6].

Table 3. Summary of estimates/assumptions for natural and fishing mortalities of bigeye tuna (adult) in other studies

	Total mortality rate (TM)	*M*	*F*	Region
Tomlinson (1996)	59 - 62%	0.4 - 0.8	0.55 - 0.20	EPO (JPN)
Boggs et al. (2000)	55%	0.4	0.38	WCPO
Hampton et al. (2003)	62.5%	0.48*	0.5	WCPO
Pan et al. (2001)	66.7%	N/A	N/A	Hawaii
This study (*at max.*)+ (*Average at MHI*)	75% (69.8%)	0.48	0.987 (0.716)	Hawaii

* Originally 0.12 per quarter in Hampton et al. (2003)

\+ The total mortality assumed in this study is for the maximum across areas and periods in 1993.

Since a typical tuna set targets BET, the catchability for yellowfin tuna (YFT) with tuna set is expected to be lower than that for BET. Following Hampton and Gunn (1998), the catchability coefficients for other species (except for BET and SWF) are assumed to be one-half of the catchability coefficient for BET ($q_{YFT} = 0.5\ q_{BET}$). Although non-target species are expected to have various q_s, declines in CPUE of those non-target species due to stock externality would have little effects on the expected revenue per set or fishers' decisions for fishing.

Estimation of auction prices of the major pelagic species

Auction prices of the major pelagic species landed by the Hawaii longline vessels were analyzed by multiple regression using monthly market data since 1993. The primary objectives of this price analysis are to (1) estimate the "expected price" to fishers, eliminating data noise, and (2) analyze the impacts of local supply on market price. Economic theory suggests that agricultural commodity market price can be modeled as a decreasing function of supply, because the total amount of agricultural production often varies due to the fluctuations in weather and other exogenous factors, including imports and export. If the effect of local supply on market price is significant, the model should incorporate a decline of fish price due to the total supply from the HILLF. Also note that the price ($/lb) of a

[4] An estimate by Adam et al. (2003), $M_{BET} = 0.65$, was higher than other estimates, maybe because most of their samples are juvenile BET caught by trollers/handliners. In general, natural mortality for juvenile tuna is believed to be generally higher than adult.

[5] Preliminary simulation results of sensitivity analysis, which are not reported in this study, indicate that alternative scenarios (e.g., TM_{max} = 70% or 80% for BET) would make no significant differences from the results in the baseline case.

[6] Nemoto (2002, p. 86) obtained a similar result, in which q_{SWF} was about twice that of a q_{BET}.

fishery/aquacultural product is often positively related to size; i.e., a larger fish or shrimp get a higher price.

Economists usually analyze the impacts of local supply of agricultural commodity on market price using "price flexibility"—the percent change in price divided by the percent change in quantity—which is the reciprocal of "price elasticity of demand". Assuming this price flexibility is constant, a Cobb-Douglas function form was used to estimate the price flexibility for each species:

$$P_{st} = A\bar{W}_{st}^{b_1}\, Q_{st}^{-b_2}\, Q_{s',t}^{-b_3}$$
$$= A\bar{W}_{st}^{b_1}\left(\bar{W}_{st}\, N_{st}\right)^{-b_2} Q_{s',t}^{-b_3} = A\bar{W}_{st}^{b_1-b_2}\, N_{st}^{-b_2}\, Q_{s',t}^{-b_3} \quad (6)$$

where

P_{st} is the average fish ex-vessel price (CPI adjusted) of species s at month t,

A is a coefficient that may be affected by several factors other than the average weight or the total supply to the local market,

$\bar{W}_{st} = Q_{st} / N_{st}$ is the average weight per fish (lb/fish), estimated as the total weight divided by number of pieces in the auction data,

Q_{st} is the total landing weight of species s at month t,

$Q_{s't}$ is the total landing weight of substitute species s'' at month t, and

N_{st} is the total number of species s supplied to the auction during month t.

Taking natural logarithms, Equation (6) for species s becomes

$$\ln P_{st} = a_{s0} + a_{s1} \ln P_{s,(t-1)} + b_{s0} \ln (Q_{st} / N_{st}) - b_{s2} \ln N_{st} - b_{s3} \ln Q_{s't}$$
$$+ d_{s1}\, D1_{st} + d_{s2}\, D2_{st} + d_{s3}\, D3_{st} + d_{s4}\, D4_{st} + e_{st} \quad (7)$$

where

a_{s0}, a_{s1}, b_{s0} ($= b_{s1} - b_{s2}$), b_{s2}, b_{s3}, and $d_{s1} - d_{s4}$: parameters to be estimated,

$P_{s,(t-1)}$: one-period lagged actual price (LAG),

$D1 - D4$: dummy variables:

$D1_t = 1$ if Jan-Mar, 0 otherwise;

$D2_t = 1$ if Apr-May, 0 otherwise;

$D3_t = 1$ if Jun-Jul, 0 otherwise;

$D4_t = 1$ if Aug-Sep, 0 otherwise.

(It implies that $D1_t = D2_t = D3_t = D4_t = 0$ during Oct-Dec).

Table 4(a). Assumed total mortality rate (TM) with the maximum fishing intensity and resulting catchability coefficient (q_s) - bigeye tuna

With Maximum Fishing Pressure				With average fishing pressure at MHI	
TM_{max}	Z_{max}	F_{max}	q_{BET}	F_{ave}	TM_{ave}
(assumed)	$= \ln[1/(1 - TM_{max})]$ [*1]	$= Z_{max} - M_{BET}$	$= F_{max} / E_{max}$	$= q_{BET} * E_{ave}$	$= 1 - e^{-(M+F_{ave})}$
38.1%	0.480	0.000	0.000000		
- - -	- - - -	- - - - - -	- - - - - -	- - - -	- - - -
50%	0.693	0.213	0.000312	0.169	47.7%
- - -	- - - -	- - - - - -	- - - - - -	- - - -	- - - -
60%	0.916	0.436	0.000639	0.345	56.2%
65%	1.050	0.570	0.000835	0.450	60.6%
67.1%	*1.112*	*0.632*	*0.000927*	***0.500*** [*2]	*62.5%*
70%	1.204	0.724	0.001061	0.572	65.1%
71.7%	*1.263*	*0.783*	*0.001146*	*0.619*	***66.7%*** [*3]
75% [*4]	1.386	0.906	**0.001328**	0.716	69.8%
80%	1.609	1.129	0.001655	0.893	74.7%
85%	1.897	1.417	0.002076	1.120	79.8%
90%	2.303	1.823	0.002670	1.441	85.4%
E_{max} =	682.53	M_{BET} =	0.48	E_{ave} =	539.57
at MHI area during period T5				Average at MHI area	

[*1] Derived from $TM = (1 - e^{-Z})$ - Equation (3)

[*2] Estimate by Hampton et al. (2003) for the entire Hawaii region

[*3] Assumption used in Pan et al. (2001)

[*4] Assumption used in the "Baseline" case of this study

Table 4(a) lists the calculated Z, F, and q values for bigeye tuna (BET) corresponding to an assumed TM_{max} value and the computed values for F and TM with the average effort level at the MHI area ($E_{ave,MHI}$). Note that the maximum effort (E_{max}) was 683 at MHI area during T5, while the average effort level at the MHI area ($E_{ave,MHI}$) was 540. These values also show that (i) for assumed TM_{max} = 67.1%, the corresponding $F_{ave, MHI}$ is 0.5, which equals the estimate in a stock assessment study of BET for the entire Hawaiian waters (Hampton et al., 2003), and (ii) for assumed that TM_{max} = 71.7%, the corresponding $TM_{ave,MHI}$ is 66.7%, which equals to a crude estimate by a NMFS biologist (Leung et al., 1999, p. 52).

However, the above estimates for TM_{max} are likely to be underestimated because fishing effort targeting BET is usually concentrated in the MHI area (i.e., 40-50% of longline sets were deployed in the MHI (Fig. 6) and hence the year-around average of TM for the MHI area ($TM_{ave,MHI}$) should be higher than the average for all areas for the HILLF. Using the midpoint of those two estimates (67.1% and 71.7%), TM_{max} is expected to be higher than 69.2%, or we can simply say that TM_{max} may be 70% or higher. On the other hand, if TM_{max} is assumed to be 80%, the corresponding $TM_{ave,MHI}$ would be 74.7%, which seems too high, compared to the estimates for the average TM value across all areas for the HILLF (62.5%-66.7%). Thus, TM_{max} is likely lise between 70 and 80%. For simplicity, we assumed that TM_{max} = 75% (and the resulting $TM_{ave,MHI}$ = 69.8%) as the "baseline" case in this study. According to the preliminary simulation results of sensitivity analysis (which are not reported in this study), alternative scenarios with TM_{max} = 70% or 80% had no crucial differences from the baseline case results.

Table 4(b) shows calculated *Z*, *F*, and *q* values for swordfish corresponding to an assumed TM_{max} value and the computed values for.*F* and *TM* with the monthly average effort level at the North Central area ($E_{ave,NC}$ = 203).

Table 4(b). Assumed total mortality rate (TM) with the maximum fishing intensity and resulting catchability coefficient (q_s) - swordfish

With Maximum Fishing Pressure				With average fishing pressure at MHI	
TM_{max} (assumed)	Z_{max} = ln[1/ (1 - TM_{max})] [*1]	F_{max} = $Z_{max} - M_{BET}$	q_{BET} = F_{max} / E_{max}	F_{ave} = $q_{BET} * E_{ave}$	TM_{ave} = $1 - e^{-(M+F_{ave})}$
27.4%	0.320	0.000	0.000000	- - - -	- - - -
- - -	- - - -	- - - - - -	- - - - - -	- - - -	- - - -
50%	0.693	0.373	0.000877	0.178	39.2%
- - -	- - - -	- - - - - -	- - - - - -	- - - -	- - - -
60%	0.916	0.596	0.001402	0.285	45.4%
65%	1.050	0.730	0.001716	0.348	48.7%
70%	1.204	0.884	0.002078	0.422	52.4%
75%	1.386	1.066	0.002506	0.509	56.4%
80% [*2]	1.609	1.289	**0.003031**	0.616	**60.8%**
85%	1.897	1.577	0.003707	0.753	65.8%
90%	2.303	1.983	0.004660	0.946	71.8%
[*3] E_{max} = 425.42 at North Ctc. area during period T5		M_{BET} = 0.32		[*3] E_{ave} = 203.08 Average at North Ctr. area	

[*1] Derived from $TM = (1 - e^{-Z})$ - Equation (3)

[*2] Assumption used in the "Baseline" case of this study

[*3] Fishing effort was standardized in terms of targeting swordfish

Kleiber and Yokawa's (2002) estimate suggested an instantaneous fishing mortality *F* = 0.05 in 1993, even though fishing effort targeting swordfish (SWF) was maximum in the HILLF. Boggs et al. (2000) had a similar result on *F*. Both studies suggest that swordfish stock in the North Pacific is unlikely to be over-exploited under the current levels of fishing effort.

Yet, in contrast to several tuna species, relatively little is known about swordfish in the North Pacific and the estimate is still preliminary (Boggs et al., 2000; Kleiber and Yokawa, 2002). For example, according to an Ecosim model by Cox et al. (2002b), *F* on average was 0.37 for SWF and greater than that for BET, which was opposite to the aforementioned stock assessment studies. Moreover, it is known that SWF is highly concentrated in a certain location and time; the annual average CPUE (number of fish caught per 1,000 hooks) for SWF with "swordfish set" mostly ranged from 14 to15 in 1990s, which was much higher than the CPUE for BET (Ito and Machado, 2001).

Therefore, it is reasonable to assume that fishing pressure on SWF at maximum, represented by TM_{max}, would be higher than those for BET at maximum, although the annual average TM for SWF is expected to be less than BET. In the baseline case, this study assumes TM_{max} for SWF to be 80% at North Central area during T1, while it assumes TM_{max} for BET be 75% at MHI during T5. In this scenario, the resulting average TM at the North Central area was 60.8% ($F_{ave,NC}$ = 0.616), which was, on the contrary, much less than the average TM at the MHI area ($TM_{ave,MHI}$ = 69.8%) for BET. As shown in Table 2, the TM and F for the entire North Pacific would be much less than those for the North Central because very few longline sets targeting SWF were deployed in the South, MHI, and Northeast areas.

The empirical model (Fig. 8) was used for nine major species in terms of ex-vessel revenue (Ito and Machado, 2001), using monthly data for Jan 1993–Dec 2001 (108 observations). From 1993 through 1999, NMFS personnel collected these data, with an auction coverage rate of about 30%. Full auction data have been provided by the dealer since January 2000. Results of the multiple regressions for these species are summarized in Table 5, and the comparisons of observed vs. predicted prices are presented in Figure 10. Note that a variable representing annual trend was not significant and therefore omitted. The model results indicate the following:

(1) Larger individuals of most pelagic species are worth more per pound, except for three large species: swordfish, blue marlin, opah (moonfish).

(2) Local supply, in general, decreases its own price, although none of the price flexibilities were elastic. The price flexibilities (in absolute term) for “local” species that are not regularly shipped to outside Hawaii (albacore, blue and striped marlin, mahimahi, opah, and ono) were relatively large (10–40%). On the other hand, the price flexibilities (in absolute terms) for BET, YFT, and SWF, which are frequently “exported”, were smaller (7.8%, 4.9%, and 3.6%, respectively) than local species. Besides, those for YFT and SWF were not significant (i.e., their p-values > 0.10).

(3) Substitution effects between certain species existed: BET on YFT price, blue marlin on striped marlin price, and mahimahi and opah on ono price. For example, a shortage (oversupply) of BET would result in higher (lower) price of YFT, and vice versa, while the supply of YFT had little effect on BET price. It indicates that BET is the primary species, while YFT is secondary in the fresh fish market (e.g., sashimi).

(4) Effects of the previous month price (LAG) were significant for all species, except for YFT and SWF. The inter-annual variation (i.e., unusually high/low price compared to the average year in the same season) was captured by this LAG variable. Significant intra-annual (seasonal) variation was also likely to exist in price of each species (except for blue marlin) because at least one of the four dummy variables was significant.

(5) Neither average weight nor local supply affected SWF price, indicating that the model in Eq. (7) did not explain SWF price well. It probably occurred because SWF is a global commodity (Ward et al., 2000) and most SWF caught by the HILLF are shipped to the mainland US market. A dummy variable was used for year 1998 because SWF price significantly fell in response to restaurant boycott and oversupply of the US

market (Kronman, 1999). The significantly positive estimates of all four dummy variables indicated that SWF price tended to be low during Oct-Dec.

(6) Overall fitness of this fish price model, represented by R^2-adjusted, ranged from 0.39 to 0.80. The model explained variation of price for blue and striped marlin and ono well (R^2-adjusted > 0.68), while moderately explaining those for the three tuna species and opah (0.44 < R^2-adjusted < 0.52). Although the R^2-adjusted in the case for mahimahi was lowest (0.39), the model was likely to be applicable since three key variables (LAG, average weight, and number of fish supplied) were significant. On the contrary, as mentioned before, one of the three key variables was significant in the case of SWF in addition to low R^2-adjusted (0.41).

Table 5. Estimates from regression analysis for market price of Hawaii pelagic species

	Bigeye tuna (BET)			**Yellowfin tuna (YFT)**			**Albacore (ALB)**		
	Coefficient	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*
Intercept	0.4386	0.5575	0.433	-0.4204	0.6085	0.491	-1.3561	1.0897	0.216
Lag	**0.3601**	0.0861	**0.000**				***0.1601***	0.0821	0.054
ln(w/n)	**0.2193**	0.1002	**0.031**	**0.5677**	0.0879	**0.000**	**0.7484**	0.2654	**0.006**
ln N	***-0.0777***	0.0335	***0.022***	-0.0494	0.0311	0.115	**-0.1739**	0.0320	***0.000***
D1	0.0522	0.0404	0.199	0.0461	0.0531	0.387	**0.2295**	0.0590	**0.000**
D2	-0.0277	0.0495	0.576	-0.0228	0.0603	0.707	-0.0259	0.0704	0.714
D3	**-0.2814**	0.0586	**0.000**	**-0.3280**	0.0726	**0.000**	***-0.1484***	0.0777	**0.059**
D4	-0.0105	0.0606	0.863	**-0.1633**	0.0726	**0.027**	0.0250	0.0713	0.727
Substitute				**ln Q_{BET}** -0.1230	0.0451	**0.008**			
R^2 adj.	0.4447			0.4499			0.4741		
F-stat	13.127			13.501			14.651		
MAPE	0.1106			0.1462			0.1675		

(Table 5 continued on next page)

(Table 5 continued)

	Swordfish (SWF)			**Blue Marlin (BM)**			**Striped Marlin (SM)**		
	Coefficient	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*
Intercept	**0.6466**	0.1852	**0.001**	2.7789	0.6451	**0.000**	2.1290	0.5376	**0.000**
Lag				**0.3230**	0.0784	**0.000**	0.3318	0.0589	**0.000**
ln(w/n)				-0.0278	0.1022	0.786	0.1957	0.1121	***0.084***
ln N	-0.0364	0.0251	0.149	**-0.3868**	0.0571	**0.000**	-0.2659	0.0375	**0.000**
D1	**0.3170**	0.0733	**0.000**	0.0535	0.0677	0.431	***0.1247***	0.0605	***0.042***
D2	**0.2110**	0.0807	**0.010**	0.0407	0.0785	0.605	-0.0178	0.0638	0.782
D3	**0.3490**	0.0782	**0.000**	0.0851	0.0724	0.242	***-0.1407***	0.0643	***0.031***
D4	**0.2196**	0.0783	**0.006**	0.1302	0.0858	0.132	0.0827	0.0761	0.280
D98	**-0.5690**	0.0801	**0.000**						
Substitute1			**ln Q_{SM}**	-0.0503	0.0409	0.221			
Substitute2						**ln Q_{BM}**	**-0.2265**	0.0469	**0.000**
R^2 adj.	**0.4190**			**0.6888**			***0.7959***		
F-stat	13.860			30.321			52.681		
MAPE	0.1912			0.1576			0.1418		

	Mahimahi (MH)			**Opah (Moonfish)**			**Wahoo (Ono)**		
	Coefficient	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*	*Coefficient*	*St. Err.*	*P-value*
Intercept	0.6104	0.4448	0.173	-1.7543	2.8469	0.539	-1.0681	0.7753	0.172
Lag	**0.2377**	0.0868	**0.007**	**0.3847**	0.0761	**0.000**	**0.2545**	0.0815	**0.002**
ln(w/n)	**0.2340**	0.1109	**0.037**	0.7127	0.5935	0.233	**0.8783**	0.2258	**0.000**
ln N	**-0.1166**	0.0299	**0.000**	**-0.2438**	0.0543	**0.000**	**-0.1607**	0.0354	**0.000**
D1	**0.1637**	0.0634	**0.011**	**0.2655**	0.0789	**0.001**	**0.2020**	0.0596	**0.001**
D2	0.0429	0.0657	0.515	0.0265	0.0844	0.754	***-0.1332***	0.0738	***0.074***
D3	0.0788	0.0665	0.239	0.0770	0.0790	0.332	-0.0273	0.0750	0.716
D4	***0.1340***	0.0675	***0.050***	**0.1863**	0.0883	**0.037**	0.0738	0.0623	0.239
Substitute1						**ln Q_{MH}**	**-0.0629**	0.0284	**0.029**
Substitute2						**ln Q_{Opah}**	-0.0650	0.0490	0.188
R^2 adj.	**0.3863**			**0.5151**			**0.7007**		
F-stat	10.531			17.087			28.573		
MAPE	0.1678			0.1826			0.1481		

Number of observations = 107 (monthly data from 1993-2001)

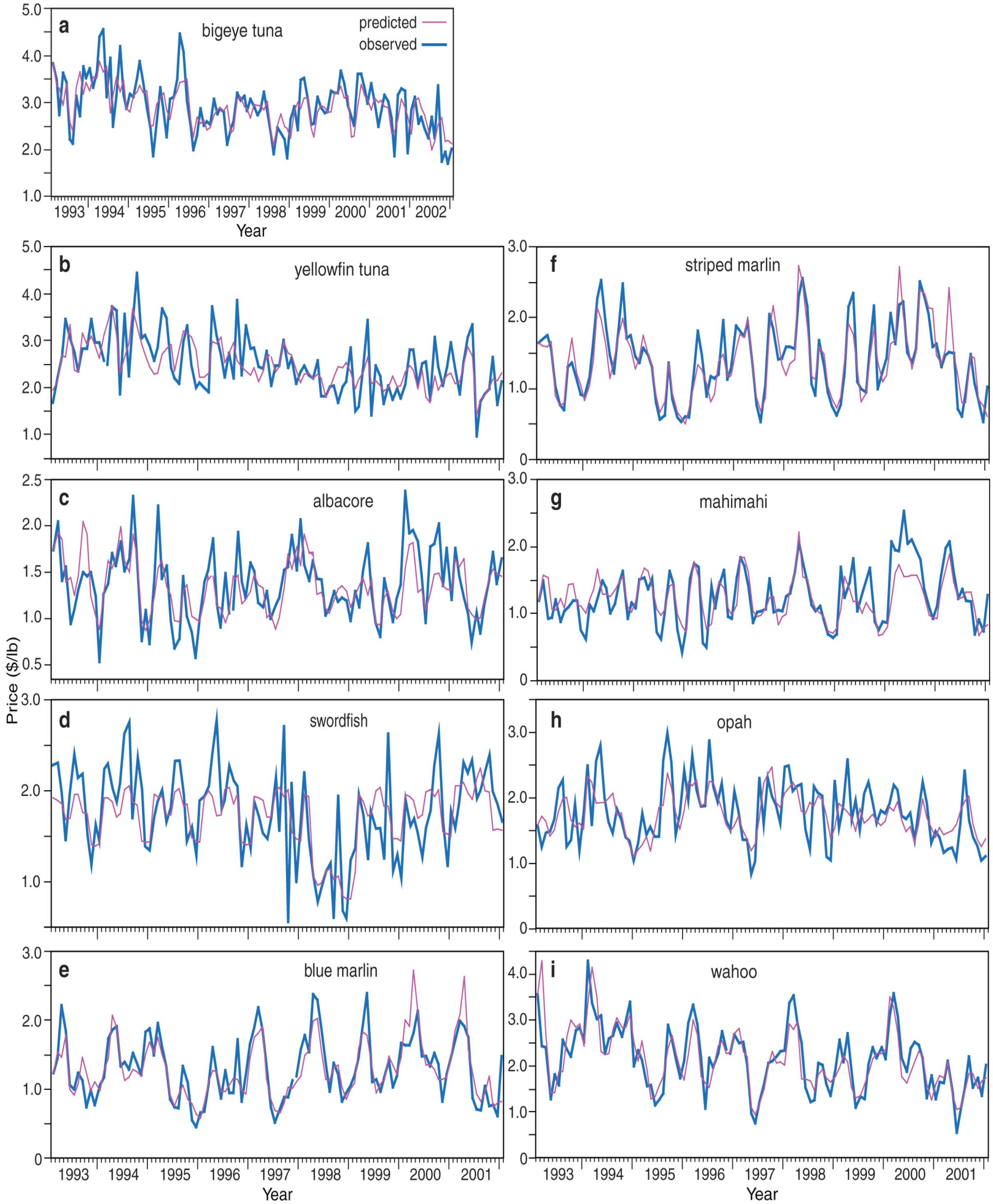


Figure 10. Monthly observed and predicted average price per year for nine species, 1993-2001 (*to 2002 for bigeye tuna).

SIMULATION RESULTS AND DISCUSSION

Effort distribution (the number of fishing sets by set type and area), the optimal numbers of longline vessels, the total number of hooks deployed, catches of the major species, and the total revenue—resulting from the simulations with the open access scenario—are summarized, and compared with the observed numbers for 1993 and 1998 in Table 6. The 1993 data set was used since the previous work (Pan et al., 2001) was done using the 1993 data, including the most complete, validated cost-earnings data (Hamilton et al., 1996). We also conducted a simulation using the 1998 data set, and used its results as the baseline case in evaluating the results of simulations for the sea turtle conservation policies, which were imposed after December 1999. In addition, while the HILLF during 1994-1998 was relatively stable without any major changes in regulatory policies, more Hawaii-based longline vessels started going to the South (Figure 6) in 1998, primarily due to the discovery of new fishing locations for BET and YFT around Palmyra. Hence, the data sets before 1998 were not very useful to estimate the stock level for South area.

In both years, the observed total effort levels were less than those in the simulation results; by 16% in terms of hooks, and by 21% (1993) and 13% (1998) in terms of sets (Table 6). In other words, the model over-allocated fishing sets by 15–27% compared to the actual data. As illustrated in Figure 2, the output of the industry fell short in reaching the optimal level predicted by the model, probably because of two reasons. First, the model assumed that the HILLF was an open access situation.[7] In reality, however, the HILLF was not exactly an "open access" situation, because competition in the HILLF might be more "oligopolistic", by the limited number of individuals/groups (where vessels within a group act as an agent). The usual effect of oligopoly is to restrict supply. In addition, potential new entries might be restricted due to unavailability of longline fishing permit and geographical isolation of Hawaii ports. Second, the model "optimally" (or efficiently) allocated longline trips without uncertainties in fish price and CPUE for each species. However, uncertainty exists in any industry. Specifically, fishers might fail to choose the best place and time for fishing to maximize their profit. They might not fully take into account the revenue from non-target species. Revenue per set[8], presented in Table 6 as a crude indicator of productivity, suggests that the actual HILLF was less productive than the simulated (optimal) results (by 1.4% in 1993 and 5.4% in 1998). The extent to which fishers are risk-averse associated with uncertainties in fish abundance and prices might discourage vessels to conduct further trips to reach the optimal level.

A major change of the HILLF from 1993 to 1998 was the shift of the primary targets toward bigeye tuna (BET): while 39% of longline sets were targeting in 1993, this percentage increased to 63% in 1998 (Table 6; see also Figure 11). Moreover, such a contrast (in which

[7] The empirical results suggested a "maximizing economic rent" scenario, which was used in Pan et al. (2001), was unlikely because the simulated total revenue and effort with the "max-rent" scenario were much less than actual data, despite having the fishing trips optimally allocated.

[8] Revenue per hook was not used here, because the major target of HILLF has really shifted to BET and a typical tuna set used nearly as twice hooks per set as a swordfish set, which could mislead the reader regarding the productivity of the HILLF.

more targeting SWF in 1993 vs. more targeting BET in 1998) was exaggerated in the simulation results: while tuna sets were only 27% of the total in 1993, the percentage if tuna sets increased to 70% in 1998 (Figure 11).

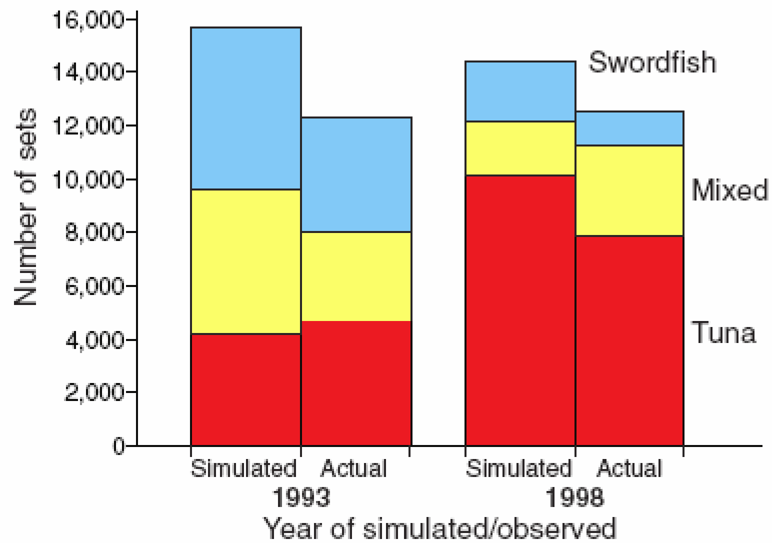


Figure 11. Numbers of tuna/mixed/swordfish sets (simulated vs. actual in 1993 and 1998).

According to the simulation results, the optimal (i.e., minimum) numbers of longline vessels for each of the three groups by vessel length (small, medium, and large) in 1993 and 1998 (Table 6) indicate that more small or medium-size vessels were preferred to large vessels in 1998, compared to 1993. It probably occurred because the model primarily relied on the cost-earning survey data in 1993 (Hamilton et al., 1996), which was likely to suggest that large vessels were more profitable by targeting SWF, while small and medium-size vessels were more profitable with tuna and mixed sets, respectively (see Table 7 for the operating costs). Tuna sets became relatively profitable under a negative atmosphere for swordfish market during 1998 (Ward et al., 2000), accompanied with higher CPUE for BET, resulting in a dramatic shift from large vessels to smaller vessels (number of large vessels: 71 → 28; the numbers of small/medium-size vessels: 15 → 38 and 56 → 79, respectively) in the simulation results.

Table 6. Comparison of simulated and actual effort allocation, catch, and total revenue

Profile	1993		1998	
	Simulated	Actual	Simulated	Actual
Revenue	68.65	53.36	56.77	46.64
($ Million)		(-22.3%)		(-17.8%)
Total hooks	15.57	13.03	20.76	17.37
(Million hooks)		(-16.3%)		(-16.3%)
Revenue per set	4.40	4.33	3.95	3.74
(x $1000)		(-1.4%)		(-5.4%)
No. of vessels				
Small	15	24	38	17
Medium	56	54	79	56
Large	71	44	28	41
Total	142	122	145	114
		(-14.1%)		(-21.4%)
No. of fishing sets per vessel	110.0	101.0	99.1	109.5
No. of fishing sets by target				
Tuna	4,179	4,747	10,066	7,865
Swordfish	6,079	4,322	2,169	1,210
Mixed	5,362	3,249	2,135	3,408
Total	15,620	12,318	14,370	12,483
		(-21.1%)		(-13.1%)
No. of fishing sets by area				
K1 (MHI)	6,033	5,134	5,236	4,439
K2 (North East)	1,730	1,055	1,182	1,201
K3 (North Center)	3,178	2,823	1,327	1,403
K4 (North West)	4,589	3,217	3,612	3,252
K5 (South)	90	89	3,013	2,188
Total	15,620	12,318	14,370	12,483
Catches of major species				
Bigeye tuna	64,801	54,803	120,809	98,856
Yellowfin tuna	19,186	16,062	22,480	21,725
Albacore	30,014	30,460	74,403	48,689
Swordfish	102,473	79,554	51,989	43,775
Blue marlin	7,098	5,124	6,964	5,348
Striped marlin	19,434	18,210	16,368	14,328

Table 7. Costs for longline operation by vessel size and set type in 1993

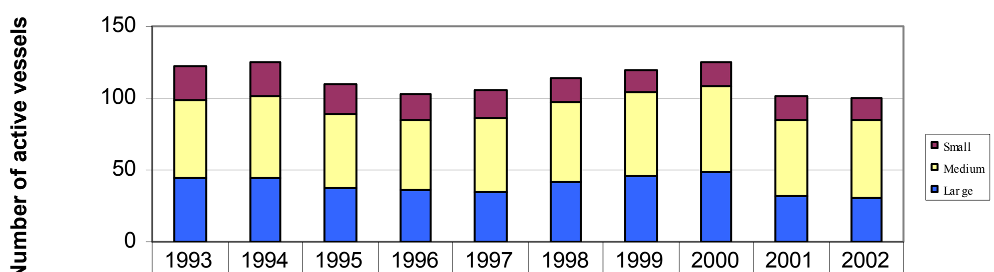
Size	Operating costs ($/fishing day) Tuna	Mixed	Swordfish	Travel cost ($/day)	Expected wage	Fixed costs ($/year)
Small	636	1,356	N/A	221	591	92,422
Medium	736	1,619	1,940	303	620	104,720
Large	908	1,950	2,043	472	694	126,619

Data source: Hamilton et al. (1996

Costs in 1998 were estimated by (i) adjusting by CPI, (ii) considering changes in the average numbers of hooks and light-sticks per set.

Expected wage is the average of the income for all crew members including captain (i.e., wage bill in $ / day at sea).

However, the above simulation results contradict the fact that the numbers of large and mediumvessels actually increased from 1996 to 2000, while the number of small vessels slightly declined (Figure 12). Moreover, more tuna sets were deployed by large and medium size vessels and in the areas other than the MHI since 1996 (Figures 13 a–c), indicating that longline vessels targeting BET recently became larger and went farther away from MHI. Longliners go to more distant water to catch BET, maybe because (i) BET CPUE in distant water might be greater than in the MHI area (Figure 14), and (ii) BET in distant water might be larger (heavier) and/or better quality, and hence get higher price ($/lb), although empirical evidence is not available yet. A large vessel (which might be equipped with more updated technology) may be preferred because it might travel faster, find fish schools more accurately, and set its gear deeper (using main line-shooter) to catch BET more efficiently. Note that vessel speed is also an important factor regarding the quality of fish meat since the shorter travel time for returning to the port would maintain fish meat fresher.



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Small	24	23	21	18	19	17	16	16	16	15
Medium	54	58	52	49	51	56	58	61	53	54
Large	44	44	37	36	35	41	46	48	32	31

Year

Figure 12. Number of active Hawaii-based longline vessels, 1993-2002.

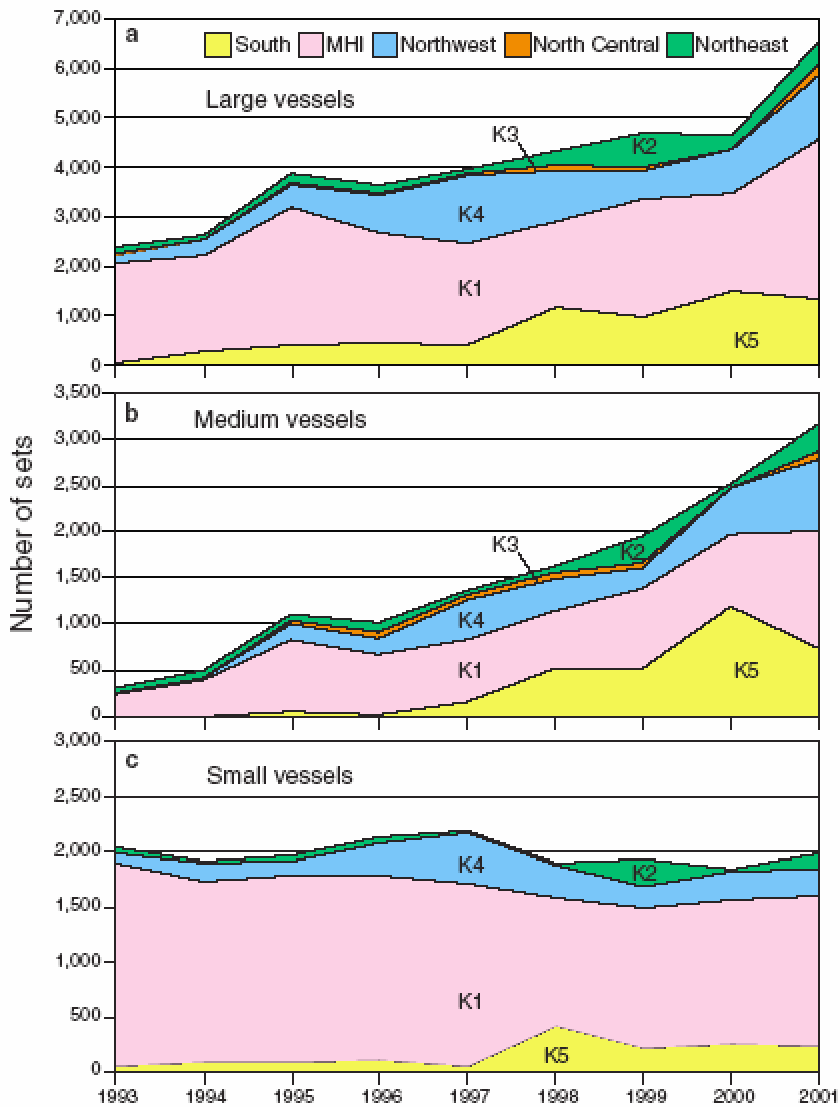


Figure 13. Annual number of tuna sets by area 1993-2001 by (a) large longline vessels, (b) medium longline vessels, and (c) small longline vessels.

Regarding spatial distribution of fishing sets, the simulation results resembled the actual events overall, except for the following; the model over-allocated longline sets to two areas, Northeast and Northwest (by more than 40%) in 1993, while it over-allocated to South (by 38%) in 1998. Although the model also predicted catches of each species well, a couple of notable prediction errors are highlighted below. In both 1993 and 1998, the simulated catches were slightly greater than the actual catches, which reflects the aforementioned fact that the simulated effort level was greater than the actual one. Swordfish catch for 1993 was overestimated (by 29%) by the simulation due to the overestimation in the numbers of swordfish/mixed sets, while the catches of BET and albacore for 1998 were overestimated due to the overestimation in the numbers of tuna sets. Although the numbers of blue marlin

(BM) caught (in terms of pieces) were smallest among the six species in Table 6, the BM catches were overestimated by more than 30% in both years.

POLICY SIMULATION RESULTS AND DISCUSSION

We examine the impacts of two aforementioned regulatory policies on the HILLF using the MMPM2 with fish prices and CPUEs for 1998 (as if these simulation results were available right before these policies were imposed). Policy 1, closure of North Central area, reallocated most of fishing sets—that are previously allocated in North Central area—to other areas. Since this closed area had been primarily for harvesting SWF, the model predicted that the closure would decrease the number of swordfish/mixed sets by 29% and catch of SWF by 30% (Table 8). Therefore, although the number of tuna sets would increase slightly, the total number of sets was expected to decrease by 9% (14,370 → 13,111). However, the total number of sets actually slightly increased from 12,483 sets (1998) to 12,899 (2000)[9]: the number of tuna sets increased by 15%, while the number of swordfish/mixed sets decreased only by 16%. Similarly, the actual number of active vessels increased from 114 (1998) to 125 (2000), despite the model predicted that the number of active vessels would decrease.

Policy 2, prohibiting all shallow sets (both swordfish and mixed types of longline sets), allowed only tuna sets. The model predicted that the total number of fishing sets would decrease by 30%, although the number of tuna sets would decrease only by 1% (Table 8). Policy 2 was likely to be more severe to the HILLF than Policy 1 since the fleet-wide revenue dropped by about 37%. Moreover, the model suggests that insufficient annual ex-vessel revenue due to the lack of income from SWF catch would result in a significant decrease in the number of vessels. It implies that several vessel-owners would exit from the HILLF because the net revenue from longline fishing accruing to them was not sufficient to cover their annual fixed costs.

However, the data for 2001 and 2002 (Table 8) show that the number of sets actually decreased only by 2.5% in 2001[10], and moreover increased by 12% in 2002, compared to the 1998 data, while the number of active vessels decreased to 100 as the model predicted. In terms of spatial distribution of longline sets, the numbers of sets allocated in MHI actually increased by about 35% in both 2001 and 2002 under Policy 2, while it was expected to decrease by 16% according to the model prediction. In addition, the number of tuna sets actually deployed in the South area (particularly in 2002) was more than predicted, despite the seasonal closure of the South area during Apr-May. Also note that the actual number of sets allocated in the North Central area in 2001 was as predicted, but it jumped up in 2002 beyond the level of the baseline case (probably because some fishers discovered good fishing spots for BET in that area).

[9] This actual number of sets allocated and the revenue generated from the HILLF in 2000 were very close to the model predictions, although it seemed to happen coincidentally.

[10] Policy 2 was actually imposed from April 2001 to March 2004, implying that the HILLF was under Policy 1 during the first quarter of 2001.

Table 8. Summary of simulation results and comparison to the actual data

	Simulation*[1]			Actual			
	Base	Policy 1	Policy 2	No policy	Policy 1	Policy 2	
				1998	2000	2001	2002
Revenue ($10^6 \$$)	56.77	50.51	35.92	46.64	50.15	33.01	37.50
		(-11.0%)	(-36.7%)		(+7.5%)	(-29.2%)	(-19.6%
Hooks (10^6 hooks)	20.76	19.69	17.00	17.37	20.24	22.34	26.89
		(-5.2%)	(-18.1%)		(+16.5%)	(+28.6%)	(+54.8%)
Revenue per set	3.95	3.85	3.61	3.74	3.89	2.71	2.68
($10^3 \$$)		(-2.5%)	(-8.6%)		(+4.1%)	(-27.4%)	(-28.2%)
No. of vessels							
Small	38	39	30	17	16	16	15
Medium	79	71	53	56	61	53	54
Large	28	23	17	41	48	32	31
Total	145	133	100	114	125	101	100
No. of fishing sets per vessel	99.1	98.6	99.5	109.5	103.2	120.6	139.8
No. of fishing sets by target							
Tuna	10,066	10,076	9,947	7,865	9,035	11,724	13,765
Swordfish	2,169	1,805	0	1,210	542	27[2]	(193)*[2]
Mixed	2,135	1,230	0	3,408	3,322	426	21
Total	14,370	13,111	9,947	12,483	12,899	12,177	13,979
		(-8.8%)	(-30.8%)		(+3.3%)	(-2.5%)	(+12.0%)
No. of fishing sets by area							
K1 (MHI)	5,236	5,214	4,400	4,439	4,689	5,998	5,941
K2 (Northeast)	1,182	1,186	677	1,201	1,935	1,031	1,128
K3 (North Central)	1,327	0	275	1,403	3	312	1,727
K4 (Northwest)	3,612	3,700	2,568	3,252	3,280	2,466	2,457
K5 (South)	3,013	3,011	2,027	2,188	2,992	2,370	2,726
Total	14,370	13,111	9,947	12,483	12,899	12,177	13,979
Catches (No. of pieces) of major species							
Bigeye tuna	120,809	116,029	95,230	98,856	74,433	78,712	140,355
Yellowfin tuna	22,480	23,282	19,121	21,725	38,363	36,857	15,782
Albacore	74,403	70,937	68,154	48,689	39,719	51,444	20,389
Swordfish	51,989	36,676	7,858	43,775	36,904	4,167	5,657
Blue marlin	6,964	6,349	5,287	5,348	4,504	6,421	3,942
Striped marlin	16,368	15,739	14,071	14,328	7,933	16,436	9,029

Policy 1: Close "North Central year-round (Dec 1999-Mar 2001)
Policy 2: No shallow sets; close South (Apr-May) (Aprl 2001-Mar
*Note 1: These simulation results are based on price and CPUE date in 1998
*Note 2: These swordfish sets were for research purposes.

Based on the structure/assumptions of the model, two possible reasons for the above prediction errors are (i) a significant deviation in CPUE and/or market price of each species from the 1998 data, and (ii) a significant change in the cost-structure and fishers' behaviors in the HILLF. First, because the BET became the primary revenue source for the HILLF after the sea turtle conservation policies were imposed, the CPUE trend of BET over the last decade was examined (Figure 14). Overall, the CPUE was higher in 1998 and 2002, than in the period 1999-2001, suggesting that the higher CPUE of BET could be the reason for a significant increase of tuna sets (15%) from 2001 to 2002.[11] Slight increases in the price ($/lb) and average weight (lb/fish) of BET from 1998 to 2000 (Figure 10, and Ito and Machado, 2001[12]) may contribute to an unexpected increase in the actual number of sets from 2000 to 2001. Yet, neither the inter-annual variation of CPUE nor higher price of BET, compared to the baseline case (1998), was likely to be the reason for considerable underestimations of longline sets in the policy simulation results, particularly for 2001. Because, in 2001, the HILLF actually maintained almost the same number of longline sets as the previous years (1998-2000) despite a substantial decrease in the fleet-wide revenue (29%). This suggests that behavior of longline vessels and costs involved in their operations could be the reasons.

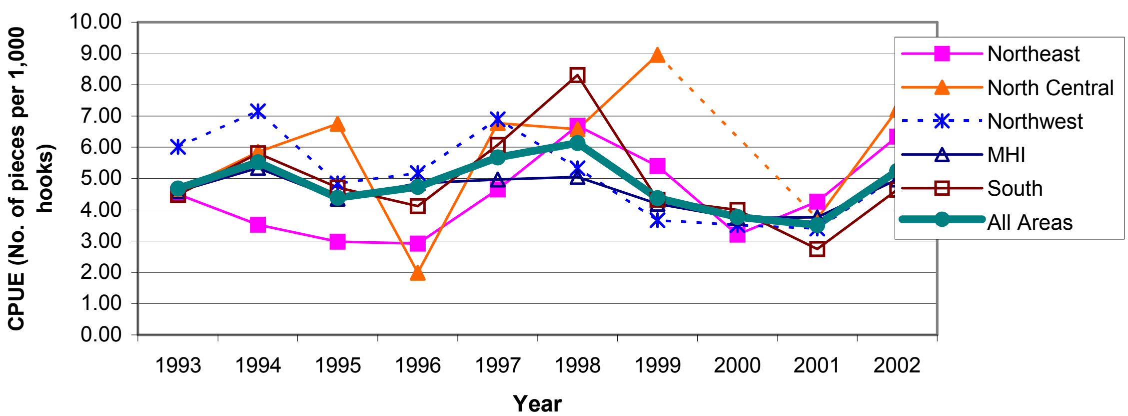


Figure 14. CPUE or bigeye tuna with tuna set, 1993-2002.

Two possible reasons for the aforementioned prediction errors are discussed below. First, this model does not incorporate the crew's labor supply behavior: i.e., the model assumes that crew would not go fishing if the expected wage is lower than a certain constant daily wage (see Equation (A1.7) in Appendix 1). However, due to the profit sharing system between the vessel's owner and crew, the crew (including captain) can be considered as a self-employed worker. Since the crew maximizes their utilities by trading off between offshore days (labor) and onshore days (leisure), they are willing to go fishing even with the lower wage if they don't have enough income from longline fishing, i.e., they are maximizing income without alternative employment opportunities (Chakravorty and Nemoto, 2001).

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[11] The BET catch from the late 2002 to the beginning of 2003 was a historical high.

[12] During 1998-2000, BET price: $3.00 → $3.60, BET average weight: 74 → 80 lb/fish

Second, some vessel-owners considerably lowered their costs of longline fishing by employing foreign crew with much cheaper wage (Allen and Gough, 2004; O'Malley and Pooley, 2003). Since those foreign crews were usually hired by monthly or annual contract (rather than sharing the net revenue with vessel's owners), the cost of hiring them is considered as a fixed cost, instead of an operating cost. This implies that replacing some (or all) crew with foreign crew would substantially reduce the operating costs, but increase fixed costs. Because the operating costs became lower, longline operation could still remain profitable despite greater short-run depletion in CPUE due to more fishing effort (implying lower ex-revenue per day). On the other hand, the higher annually fixed costs will give incentives to a vessel-owner for forcing crew to working more days annually, or leave the industry (and disincentive to enter the industry)[13].

The actual data in Table 8 show that the average annual number of fishing sets per vessel substantially increased from 103 to 140 during 2000-2002,[14] while the number of active vessels dropped to 100. In addition, the revenue per set decreased by 28% from 1998 to 2002. According to those indicators, there is the evidence of the "foreign crew" effect. Thus, the employment of foreign crew is likely to be the primary reason for allowing the HILLF to sustain or even increase fishing effort despite a substantial decrease in the fleet-wide revenue due to the tight regulation (Policy 2).

As mentioned before, fluctuation in BET stock (i.e., CPUE) in the North Pacific significantly affected the cost-earnings situation of the HILLF. As shown in Figure 14, the CPUE of BET considerably fluctuated with certain patterns. To improve the accuracy of the model predictions, the model should incorporate results from other studies that have forecasted the CPUE of BET and other major species in Hawaii, such as Howell and Kobayashi (2004).

Finally, note that the catch of BET as well as the number of longline sets targeting BET had substantially been increased, as results of the recent turtle conservation policy, which caused a suspension of swordfish-targeted activity from the HILLF. Moreover, recent stock assessment studies (Boggs et al., 2000; Hampton et al. 2003) suggest that the BET stock in the western and central Pacific Ocean may be regionally overfished. These facts suggest that catch of BET and effort targeting this species may need be cautiously monitored and analyzed. Meanwhile, the effectiveness of the recent policy in terms of protecting sea turtles from interaction with longline hooks (in particular, those of foreign vessels) is questionable (Kaneko and Bartram, 2003). Therefore, it could be worth considering a policy that would mitigate the fishing pressure on BET (e.g., reopening swordfish fishery in the HILLF with certain restrictions[15]), as long as incidental sea turtle takes could be precluded from increasing significantly.

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[13] According to Allen and Gough (2004), personal communication with Gough, a foreign crew costs $400-$600 per month, and roughly costs $10,000 annually (during 2000-2002), although the cost varies depending on situation. According to Hamilton et al. (1996) and O'Malley and Pooley (2003), a longline crew, on average, earned about $20,000 in 1993 and $27,000 in 2000 annually from tuna trips.

[14] Foreign crews must stand-by due to immigration laws (Allen and Gough, 2004), which may make it easy for a vessel to take a fishing trip promptly. This may be another reason for this increase.

[15] New regulation policy to permit the Hawaii longliners to target swordfish was imposed after April 2004.

CONCLUSION

We have enhanced a mathematical programming model developed by Pan et al. (2001) to evaluate the economic impacts of recent sea turtle conservation policies on the HILLF, as follows. First, we adopted an alternative catch function employed commonly in stock assessment and ecological studies to establish a linkage to results of those studies, so that the model could be used in the context of ecosystem-based fishery management. Second, predicted prices of nine major pelagic species in Hawaii, resulting from multiple regressions, were used as a proxy for “expected” fish prices. This price analysis also indicates that (a) larger fish are, in general, worth more, and (b) local supply decreases auction prices, in particular, of “local” species, which are not regularly shipped to outside Hawaii. The model implies that the net economic return would diminish due to declines in (i) CPUEs and (ii) fish prices, as it allocates more longline trips across areas and periods. Then it obtains an economic equilibrium, as it continues to allocate trips until the net returns accruing to crew and vessel-owners would equal their expected wage and the annual fixed costs of longline vessel, respectively.

Overall, the simulation with an open access scenario accurately replicated effort distribution by area, period, and target in 1993 and 1998, but the actual number of longline sets was slightly less than the model predicted. This error occurred because the model took no account of imperfect competition or inefficient allocation of longline sets. Results from two policy simulations for sea turtle conservation, however, indicate the total number of longline sets was actually much more than the model predicted; in fact, it even increased despite a significant revenue loss by the tight regulation. This prediction error was probably due to a considerable reduction in the costs involved in longline operations by employing foreign crew. In addition, the variation in CPUEs and market prices of major species in the HILLF was likely to contribute to the prediction error.

The model demonstrated its usefulness in analyzing the impacts of various regulatory policy options for the HILLF. To improve the accuracy of the predictions, the model needs to incorporate updated information from socioeconomic studies (e.g., Allen and Gough, 2004) and stock assessment/forecast (e.g., Howell and Kobayashi, 2004).

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APPENDIX 1

Mathematical model formula for the MMPM2

Objective Function

Maximize the total revenue (Open Access)

$$Max \sum_i \sum_j \sum_k \sum_t Y_{ijkt} N_{ijkt} \tag{A1.1a}$$

allocate N_{ijkt}

The following function—*maximizing the industry's rent*—was used in Pan et al. (2001):

$$Max \sum_i \sum_j \sum_k \sum_t R_{ijkt}\, N_{ijkt} - \sum_i \sum_j \sum_k \sum_t \omega_i \left(d_{ijkt}^{Fh} + d_{ik}^{Tl} \right) N_{ijkt} - \sum_i Fc_i\, V_i \tag{A1.1b}$$

Constraints

Vessel constraints (sufficient vessels needed to take fishing trips)

$$\sum_j \sum_k N_{ijkt}\, (d_{ijkt}^{Fh} + d_{ik}^{Tl} + d_{ijk}^{Rn}) \le V_{it}\, L_t \tag{A1.2}$$

$$V_{il} \le V_i \tag{A1.3}$$

* In the "Open Access" Case (1b), V_{it} and V_t have no upper limits, while the optimal trip allocation N_{ijkt} is determined. Therefore, the minimum values for these two variables are adopted. That is,

$$V_{it} = \frac{1}{L_t} \sum_j \sum_k N_{ijkt}\, (d_{ijkt}^{Fh} + d_{ik}^{Tl} + d_{ijk}^{Rn})$$

$$V_i = \underset{t}{Max} \left(V_{it} \right)$$

Stock constraints (industry cannot catch species s more than the stock)

$$\sum_i \sum_j \left[CPUE_{sijkt} \cdot \left(u_{ij}\, d_{ijkt}^{Fh}\, N_{ijkt} \right) \right] \Big/ Mo_t \le X_{skt} \tag{A1.4}$$

Micro-level Entry Conditions

Trip-entry condition

$$R_{ijkt}\, N_{ijkt} \geq 0 \tag{A1.5}$$

Owner-entry condition (annual level)

$$\left(\sum_j \sum_k \sum_t (1-\lambda_i)\, R_{ijkt}\, N_{ijkt} - Fc_i \right) V_i \geq 0 \tag{A1.6}$$

Crew-entry condition (annual lev*el)*

$$\left(\sum_j \sum_k \sum_t \lambda_i\, R_{ijkl}\, N_{ijkl} - \omega_i \left(d_{ijkt}^{Fh} + d_{ik}^{Tl} + d_{ijk}^{Rn} \right) N_{ijkt} \right) V_i \geq 0 \tag{A1.7}$$

Indices, Variables, and Parameters

Five-dimensional indices of variables

i = fleet, {*i*: 1, …, I} (1: small, 2: medium, and 3: large longline);
j = set type (target), {*j*: 1, …, J} (1: bigeye tuna, 2: mixed, 3: swordfish);
k = area, {*k*: 1, …, K};
t = period (or season), {*t*: 1, …, T};
s = species {s = 1, …, S}

Variables

V_{it} : Number of vessels of fleet *i* during period *t*;
V_i : Annual fleet size (number of vessels) of fleet *i*;
N_{ijkt}: number of trips of fleet *i* targeting *j* in area *k* during period *t* (trip);
$\left(d_{ijkt}^{Fh}\, N_{ijkt} \right)$: number of sets of fleet *i* targeting *j* in area *k* during period *t*;
E'_{jkt}: monthly average effort (not standardized) in area *k* during period *t*;

$$E'_{jkt} = \sum_i \frac{u_{ij}\, d_{ijkt}^{Fh} N_{ijkt}}{Mo_t} \tag{A1.8a}$$

E_{kt}: standardized effort in area *k* during period *t* (see Appendix 4 for details):

$$E_{kt} = \sum_j \theta_{sj}\, E'_{jkt} \tag{A1.8b}$$

Z_{skt}: Instantaneous mortality rate: $Z_{skt} = M_s + q_s\, E_{kt}$ (A1.9)

α_{skt}: CPUE coefficients: $\alpha_{skt} = \dfrac{1-e^{-Z_{skt}}}{Z_{skt}}$ (A1.10)

$CPUE_{sijkt}$: catch-per-unit-of-effort (CPUE) for species *s* for fleet *i* targeting species *j* in area *k* during period *t* (fish/effort) with standardized effort E_{kt}.

$$CPUE_{sijkt} = CPUE^{0}_{sijkt} \cdot \alpha_{skt} \quad \text{(A1.11)}$$

Y_{ijkt}: ex-vessel trip revenue (\$/trip): $Y_{ijkl} = \sum_{s} P_{sjt}\left(u_{ij}\, d^{Fh}_{ijkt}\, CPUE_{sijkt}\right)$ (A1.12)

R_{ijkt}: trip net revenue (\$/trip): $R_{ijkl} = \left(1-\tau_i\right)Y_{ijkt} - Co_{ijkt}$ (A1.13)

Parameters

L_t: Length (number of days) of period *t*;
Mo_t: Length (number of months) of period *t*: $Mo_t = \{1, 2, 3, \text{or } 4\}$;
d^{Fh}_{ijkt}: Number of fishing days per trip;
d^{Tl}_{ik}: Number of traveling days per trip;
d^{Rn}_{ijk}: Number of turn around days per trip;
$d^{Fh}_{ijkt} + d^{Tl}_{ik}$: Trip length (days at sea) per trip;
u_{ij}: Amount of unit effort (1,000 hooks for longline) per fishing set;
τ_i: Tax and fee rate (10.5% as the total) for fleet *i*;
Fc_i: Fixed costs, include opportunity costs of investment, depreciation, maintenance, and insurance (\$/year);
Co_{ijkt}: Operating costs per trip (\$/trip) is the sum of fishing, traveling and turn-around costs; $Co_{ijkt} = Cf_{ijkt}\, d^{Fh}_{ijkl} + Ct\, d^{Tl}_{ik} + Cr_{ijk}\, d^{Rn}_{ijk}$
P_{sjt}: Fish price for species *s* caught by longline trip targeting *j* during period *t* (\$/fish);
λ_i: Crew share of net revenue for fleet *i* ;
$(1 - \lambda_i)$: Owner share of net revenue for fleet *i*;
ω_i: Expected wage per working day (day at sea) for all crew members (including captain) of a vessel in fleet *i* (\$/day);
q_{sjk}: Catchability coefficient of species s by set targeting *j* at area *k*;
X_{skt}: Stock of species *s* in area *k* and period *t* (fish); see Appendix 2
$CPUE^{0}_{skt}$: Initial CPUE level (fish/effort); see Appendix 2.

APPENDIX 2

Derivation of the catch function

The catch function (1) can be transformed to

$$CPUE_{skt} = \frac{C_{skt}}{E_{kt}} = \left(\frac{q_s\, E_{kt}}{Z_{skt}}\right)\frac{\left(1-e^{-Z_{skt}}\right)X_{skt}}{E_{kt}} = X_{skt}\, q_s \frac{\left(1-e^{-Z_{skt}}\right)}{Z_{skt}} \qquad \text{(A2.1)}$$

Recall $Z_{skt} = M_s + q_s\, E_{kt}$ (Equations 2a and 2b). Now define □$_{skt}$ as

$$\alpha_{skt} = \begin{cases} \left(\dfrac{1-e^{-Z_{skt}}}{Z_{skt}}\right) & if\ Z_{skt} > 0 \\ 1 & if\ Z_{skt} = 0. \end{cases} \qquad \text{(A2.2)}$$

Note: expanding $\left(1-e^{-Z_{skt}}\right)$ around zero (Z_{skt} = 0) in the above equation as a Taylor series, the equation can be transformed as follows:

$$\lim_{Z \to +0} \frac{1-e^{-Z}}{Z} = \lim_{Z \to +0}\left(1-\frac{Z}{2!}+\frac{Z^2}{3!}-\frac{Z^3}{4!}+\cdots\right) = 1, \qquad \text{(A2.3)}$$

implying that α in Equation (A2.2) is a continuous function of effort Z_{skt} even around zero since M_s is constant. Furthermore, if both M_s and E_{kt} are almost equal to zero (in the absence of mortality), then $\alpha_{skt} \cong 1$, and hence the CPUE for the first set would be greatest as $CPUE^0_{skt} = X_{skt}\, q_s \cdot 1$, implying that $CPUE^0_{skt}$ is independent of effort level, and reflects only fish abundance. Then CPUE profile function (A2.1) can be simplified as

$$CPUE_{skt} = CPUE^0_{skt} \cdot \alpha\left(Z_{skt}\right), \qquad \text{(A2.4)}$$

implying that the coefficient □$_{skt}$ measures the decline of CPUE due to fishery catch in the short run.

APPENDIX 3

Comparison of the CPUE profile with the previous study (Pan et al., 2001)

$$
\begin{aligned}
C_{skt} &= CPUE_{skt} \cdot E_{kt} \\
&= \left(CPUE^0_{skt} \cdot \alpha_{skt} \right) E_{kt} \qquad \text{(A3.1)}
\end{aligned}
$$

DCR1 (Pan et al. 2001)	DCR2 (this study)	
$\alpha_{skt} = 1 - \left(\frac{C_{skt}}{X_{skt}} \right)^{10}$	$\alpha_s \left(E_{kt} \right) = \frac{1 - e^{-\left(M_s + q_s E_{kt} \right)}}{\left(M_s + q_s E_{kt} \right)}$	(A3.2)
Estimation of Initial Stock $\hat{X}_{s,k,t}$ and $CPUE^0_{skt}$		
$\hat{X}_{skt} = \frac{3}{2} C^A_{skt}$	$\hat{X}_{skt} = \frac{C^A_{skt}}{1 - e^{-\left(M_s + q_s E^A_{kt} \right)}}$	(A3.3)
(Stock is assumed to be 150% of actual catch)	(Stock depends on effort level)	
$CPUE^0_{skt} \cong CPUE^A_{skt} = \frac{C^A_{skt}}{E^A_{kt}}$	$CPUE^0_{skt} = \hat{X}_{skt}\, q_s$	(A3.4)
	or $= \frac{CPUE^A_{skt}}{\alpha_s \left(E^A_{kt} \right)}$	

Note 1: Subscripts i, j (vessel length and set type) are ignored here to simplify the comparison.

Note 2: Superscript ^{A} indicates actual (or observed) data for each variable. A "hat" mark on the top of a parameter indicates that the value of parameter is estimated in this study before running the model, rather than given from the theory or outside sources.

Note 3: Strictly speaking, the initial CPUE level ($CPUE^0$) in Equation (A3.4.1) should theoretically be 1.8% higher than the actual CPUE level, although this slight difference was ignored in Pan et al. (2001).

APPENDIX 4

A procedure to standardize fishing effort

For simplicity, assuming that there are only two set type, targeting bigeye tuna (BE) or swordfish (SW), instantaneous fishing mortality rare F_{skt} is expressed as

$$F_{skt} = q_{s,'BE'}\,E_{'BE',k,t} + q_{s,'SW'}\,E_{'SW',k,t}$$

$$= q_{s,'BE'}\left[E_{'BE',k,t} + \left(\frac{q_{s,'SW'}}{q_{s,'BE'}}\right)E_{'SW',k,t}\right] \qquad \text{(A4.1)}$$

where $q_{s,j}$ is a catchability coefficient for species s targeting j. By defining the catchability ratio as $\theta_s = \dfrac{q_{s,'SW'}}{q_{s,'BE'}}$, equation (A4.1) can be simplified as

$$F_{skt} = q_{s,'BE'}\left(E_{'BE',k,t} + \theta_s\,E_{'SW',k,t}\right) = q_{s,'BE'}\,\tilde{E}_{s,k,t} \qquad \text{(A4.2a)}$$

where $\tilde{E}_{s,k,t}$ is a standardized effort for species s. However, practically, the following formula is more useful for swordfish (s = 'SW' and j = 'SW"):

$$F_{'SW',k,t} = q_{'SW','SW'}\left(\frac{E_{'BE',k,t}}{\theta_{'SW'}} + E_{'SW',k,t}\right) = q_{'SW','SW'}\,\tilde{E}_{'SW',k,t}\,, \qquad \text{(A4.2b)}$$

because θ_s is quite large (greater than 30, indicating a tuna set catches very few swordfish), and then the left-hand side term in the parenthesis will be very small. Also note that (i) E_{kt} in the main text of this paper indicates a standardized effort, and (ii) this "catchability ratio" θ_s for species s was estimated using a method developed by Nemoto (2002), and (iii) Equations (A4.2a and b) should include effort by mixed sets for actual computation of F_{skt}.