Evaluation of Fishing Opportunities under Sea Turtle Interaction Limits —A Decision Support Model for Hawaii-based Longline Swordfish, *Xiphias gladius,* Fishery Management

MINLING PAN and SHICHAO LI

ABSTRACT—Conservation measures of setting annual caps on sea turtle, Cheloniidae, interactions and other regulations have resulted in a significant reduction in sea turtle interactions in the Hawaii-based longline fishery. On the other hand, the conservation measures created a limitation on swordfish, Xiphias gladius, *production and created uncertainty for participants in the fishery because the fishery would be closed whenever the cap is reached. This study explores the trade-offs between the risks of sea turtle interactions and economic returns from swordfish fishing, and identifies examples of alternative management options that could allow the swordfish fishery to operate throughout the year with a reduced risk of exceeding the cap on loggerhead sea turtle,* Caretta caretta, *interactions. In addition, the study compares the trade-offs in terms of foregone swordfish production based on one interaction reduction before and after the implementation of the conservation measures. A spatial bioeconomic model is developed to conduct simulation analyses. A Generalized Additive Model (GAM) is applied to Hawaii longline logbook data to examine and predict sea turtle interactions in response to changes in spatial and temporal distributions of fishing effort and oceanographic conditions. A cost function is built into the model for making economic analyses to estimate net revenue returns.*

Introduction

The Hawaii shallow-set longline fishery primarily targets swordfish, *Xiphias gladius*, in waters north of the Hawaiian Archipelago. These fishing grounds are also key pelagic habitat for protected species of sea turtles, particularly loggerhead sea turtles, *Caretta caretta*, and occasionally longline vessels will incidentally catch them. In 2004, under provisions of the Endangered Species Act, NOAA's National Marine Fisheries Service (NMFS) issued a series of regulations for the fishery including caps on incidental captures of sea turtles (called sea turtle "interactions") allowed each year (NOAA, 2009). These regulations included an annual fishing effort limit which is the total number of fishing days (sets) that the fleet could utilize throughout the year. If and when the fleet-wide fishing effort limit is reached, or the incidental sea turtle catch limit is reached, NMFS will close the swordfish fishery for the remainder of the year. Subject to these constraints, and other regulations, swordfish vessels are free to set their gear in any month and anywhere in the swordfish grounds.

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The location and timing of swordfish fishing operations has consequences for sea turtles as well as for the economic returns of the vessels. Decisions on where and when to fish take into account expected swordfish catch rates and may take into account the likelihood of interactions with sea turtles, both of which vary spatially and temporally, as well as the costs incurred in fishing, which are largely a function of trip length (days) and distance of fishing locations from port.

Two natural questions that arise are "can sea turtle hot spots be identified and avoided without reduced or negative impact on the economic returns of the fishery?" And, if so, "what time-area fishing strategy should be pursued to maximize net economic returns subject to the fleet-wide constraint on turtle interactions and fishing effort?" To study these questions from a fleet-wide perspective, a bioeconomic model was developed and used to examine trade-offs between the risk of interacting with sea turtles and economic returns to the fleet (Li and Pan, 2007).

This paper describes the bioeconomic model and demonstrates how it can be applied to evaluate potential policy choices. The model was used to search for possible policy alternatives in order to maximize swordfish fishing opportunities subject to the constraints on fishing effort and the annual cap on interactions with loggerhead sea turtles. If the swordfish fishery is closed, Hawaii longline fishermen who are engaged in the shallow-set fishery for swordfish can redirect their effort to target bigeye tuna, *Thunnus obesus*, using deep-set longline gear. Thus, the foregone swordfish fishing opportunity may not have a negative impact on the Hawaii longline fishery if fishermen could continue their fishing operation by targeting bigeye tuna for the remainder of the year (at some fixed and operational costs).

However, the fishery also faces restrictions on bigeye tuna due to overfishing of the stocks in the Pacific Ocean.[1] Reduced fishing opportuni-

[1]Bigeye catch limits imposed on the Hawaii longline fishery are determined by two Regional Fisheries Management Organizations (RFMO's): the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC). Each RFMO allocates a region-specific bigeye quota for the U.S. pelagic longline fishery operating in its

ties in the tuna sector caused by bigeye tuna quotas imply an increased importance of fishing opportunities in the swordfish sector. Therefore, developing an analytical tool that facilitates the formulation of an ecologically sustainable and responsible fishery for swordfish is of vital importance for Hawaii's longline fishery as a whole.

A Generalized Additive Model (GAM) was developed by Kobayashi and Polovina (2005) to predict sea turtle interaction rates by month and location. The model was used to estimate the impacts on the fishery landings and sea turtle interactions for certain area closures. However, the model has several limitations, such as omitting fishing costs, and the spatial and temporal variations of fish catch rates. Modifications were made to improve the model for this policy analysis

For example, the NMFS Turtle-Watch Program (Howell et al., 2008) generates maps of sea surface temperature in the Hawaii longline swordfish fishing grounds and delineates areas where interactions with sea turtles are considered most likely to occur. If these areas with high interaction rates are closed to the fishery, what would be the economic impact to the fishery, and would the sea turtle interactions be at risk to exceed the caps or not?

This study aims to develop a model to enhance quantitative analyses for the decision-making process. We proceed by updating and modifying the GAM model, illustrating the tradeoffs between sea turtle interactions and economic returns under different fishing operations, and then search for optimal policy options with different area closure and/or seasonal closures.

Model Development

Loggerhead sea turtle interactions were the main concern to the Hawaii longline swordfish fishery due to the high interaction rate, even though the fishery also interacted with other sea turtles. Because areas with high catch rates of swordfish often overlap with loggerhead sea turtle habitat, the optimization of a time-area fishing strategy involves a trade-off between potential economic returns and impacts on the turtles.

To help understand the trade-off, we developed a spatial and temporal model of longline–turtle interactions that would enable prediction of sea turtle interaction rates associated with each unit of swordfish fishing effort and the economic returns of the fishing effort by area and time. The model was developed to predict sea turtle interaction rates because sea turtle interactions were a rare event and no complete record of longline–turtle interactions existed for all fishing trips, only those monitored through the observer program administered by the NMFS Pacific Islands Regional Office.

We used the GAM approach developed by Kobayashi and Polovina (2005) to build a spatial and temporal bio-economic model to predict sea turtle interaction rates by month and location of fishing, and to evaluate the policy options of time-area closures to reduce the overall level of interactions. There are several limitations in the Kobayashi and Polovina (2005) model, so modifications were made to improve the model for the policy analysis.

First, this study developed the GAM to predict fish catch per unit of effort (CPUE) (measured per 1,000 hooks in this study) by month and location of fishing, for the targeted species (swordfish) and other fish species caught during the fishing trip. Thus, the revenue associated with the fishing effort in different times and areas can be calculated with fish catch and fish price data, reflecting the spatial and temporal variation of fish catch rates. Economic returns are represented by ex-vessel net revenue[2] per 1,000 hooks deployed. Kobayashi and Polovina (2005) used GAM fitted to the data to predict turtle interactions given specified levels of fishing effort over the entire longline fleet, assuming no spatial and temporal variations for fishing effort and CPUE.

In the analysis of Kobayashi and Polovina (2005), economic returns in the longline fleet were based only on revenue. A better measure of economic returns would take into account fishing costs, in particular the costs of travel to and from the fishing grounds, which can be greatly affected by time-area regulations, fish distribution, fuel costs, and other factors. Even a 1-day increase in travel time per trip can result in a significant loss in net annual revenue (Hamilton et al., 1996).

To incorporate such economic factors, we used trip cost data for the period of 2005–06 gathered with an economics data collection program established through a collaboration between the NMFS Pacific Islands Fisheries Science Center (PIFSC) Economics Program and the Pacific Islands Regional Office (PIRO) (Pan et al.[3]) and developed a cost function associated with each production unit (fishing trip). The summary of the cost data was posted on the PIFSC website (PIFSC[4]) although the details of individual trips and the associated revenue

area of jurisdiction. The Eastern Pacific Ocean quota was 150 t during 2004–06, and 500 t after 2007 (applied to vessels that were longer than 24 m). The annual bigeye tuna quota had been 3,763 t since 2009 and further declined in 2015.

[2]The ex-vessel revenue of each set was calculated by using the monthly piece value for each species of fish sold ($/fish using fish auction data) multiplied by the number of fish caught and kept for a particular set as recorded in Hawaii longline logbook datasets (unpubl. confidential data by PIFSC). Monthly ex-vessel piece values of all the species caught and sold (28 species in total) from Hawaii longline logbook data were calculated based upon 2005 Honolulu auction data (source: Pac. Isl. Fish. Sci. Cent. unpubl. confidential data). The cost of each fishing trip was estimated from the regression model based on its set type, fishing days, vessel length, and average distance from set location to the port of landing recorded in the fishermen's logbooks. Economic returns in net revenue for each effort unit (set) was then calculated from ex-vessel revenue by subtracting the estimated variable costs, and then adjusted for the number of hooks deployed in the set.

[3]Pan M., H. L. Chan, and K. Kalberg. 2012. Tracking the changes of economic performance indicators for the main U.S. commercial fisheries in the Pacific Islands Region. Pac. Isl. Fish. Sci. Cent. Inter. Rep. IR-12-039, Issued 15 Oct. 2012, 18 p.

[4]PIFSC. 2011. Data summary of the unpublished confidential data was presented in the economic performance of Hawaii longline fishery. Pac. Isl. Fish. Sci. Cent. rep. online at: http://www.pifsc.noaa.gov/economics/economic_performance_of_the_hawaii_longline_fishery.php, accessed 1 Apr. 2014.

Table 1.—Regression coefficients of the log-transformed trip-cost function.[1]

Variables	Coefficients	Standard error	*P*-value	Adjusted R^2
Intercept	3.50558	0.0504	0.000	0.803
Fishing days (#sets)	0.02126	0.0021	0.000	
Average-distance (Miles from port)	0.00012	3.4E-05	0.001	
Vessel length (feet)	0.00529	0.0008	0.000	
Set type	0.19984	0.0195	0.000	

[1]Cost per (fishing) trip as a function of predictor variables. Number of observed trips = 181. Set type is a dummy variable (deep set = 0; shallow set = 1) in the model. *P*-values indicate all variables are significant at least 99% confidence level. Data source: Data of trip cost, fishing days, and travel distance were from PIFSC unpublished confidential data.

were not published since they were confidential data.

Table 1 shows the results of a linear regression analysis on the cost function for the fishery based on 181 observed trips, including both shallow-set swordfish trips and deep-set tuna trips, which revealed that trip costs were significantly affected by set type (targeting tuna or swordfish), days of fishing per trip, vessel size (length), and the average distance to port from the fishing location. The predictor variables are available from the mandatory logbooks of daily fishing activity submitted to NMFS by vessel captains or in NMFS permit databases, or can be calculated from such information.

Therefore, using the cost function resulting from the regression analysis (Table 1), the cost of each fishing trip of the fleet can be estimated based on its set type, trip days, vessel size, and the distance from port. Using this as the cost function incorporated into the spatial and temporal GAM model, the economic return of fishing effort was measured by net revenues[2], ($/1,000 hooks deployed). Because monthly prices and fish catch rate were used in the revenue calculation, the variation of revenue across months was considered in the model.

Lastly, data for the period of 2000–06 were included in the model. Kobayashi and Polovina (2005), using 1994–99 observer data, examined sea turtle interactions in relation to oceanographic conditions and spatial and temporal distributions of fishing effort. The Hawaii longline fishery experienced many changes, including the closure of the swordfish fishery in 2000 and its reopening in 2004, resulting in much lower sea turtle interaction rates than prior to 2000. In addition, the focus of this study was on the swordfish fleet using shallow-set gear, while the Kobayashi and Polovina (2005) model used all the observed Hawaii longline fishing operations, including those by vessels using deep-set gear to target bigeye tuna along with those using shallow-set gear to target swordfish.

Based on our modified GAM model with updated data in this study, loggerhead turtle interactions were found to be significantly associated with many factors including: season (month) and year, latitude and longitude of fishing, type of longline set (either a deep-set operation for tuna or shallow-set operation for swordfish), sea surface temperature, and even moon phase. The variables significantly associated with loggerhead interaction rates were consistent with those found by Kobayashi and Polovina (2005).

The updated GAM is used to estimate turtle interactions per unit of fishing effort (longline set) in different locations (using one degree by one degree latitude/longitude squares) and in different months. Hence, model predictions can be generated for the total number of sea turtle interactions that might be expected for any given effort level (total number of swordfish sets) and any given effort distribution across months and locations. Thus, the model can be used to investigate the trade-offs between sea turtle interactions and economic returns to the fishery for different policy simulations and search for the possible optimal solutions under the two conflict management goals of maximum fishery economic return and minimum sea turtle interactions.

Simulations and Results

The Trade-offs Among Seasons and Areas

Because of the spatial and temporal variations in sea turtle interaction rates and economic returns, the model predicted different economic returns and turtle interaction levels between seasons and areas. The model results show that sea turtle interactions and economic returns showed similar patterns (increasing or decreasing together) in some months, but showed different patterns in other months (Fig. 1).

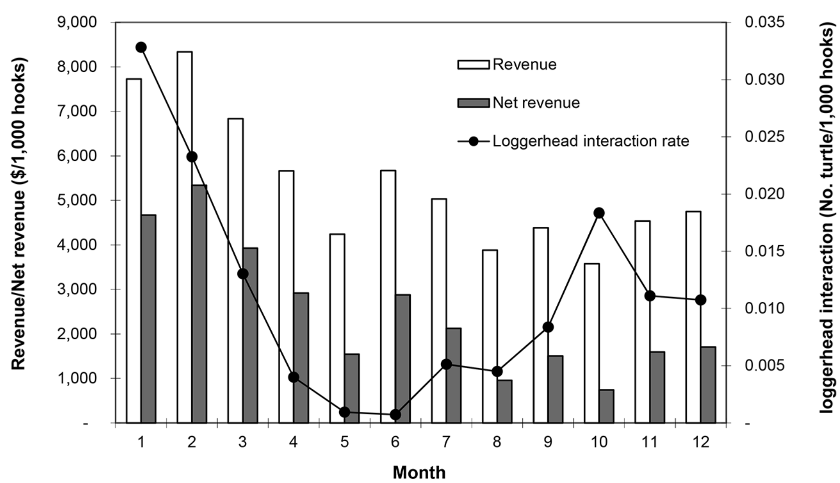

Figure 1.—Economic returns and loggerhead turtle interactions across a 12-month period.

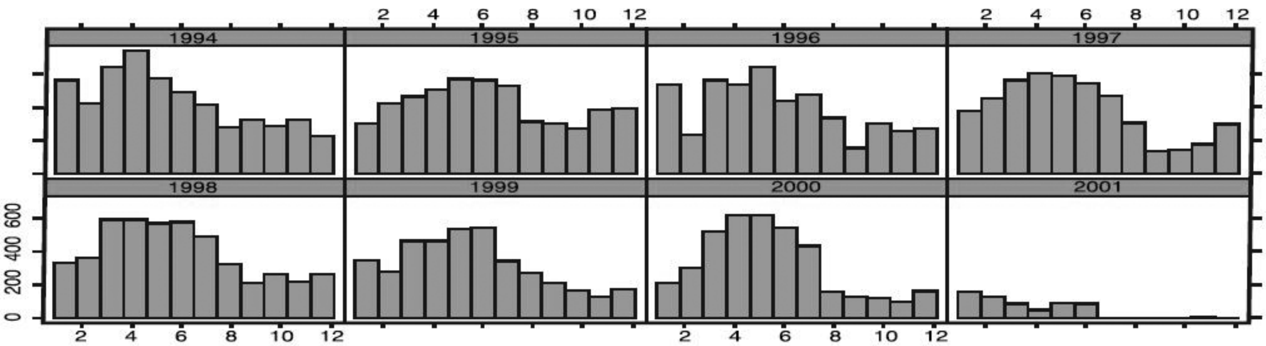

Figure 2.—Monthly distribution of swordfish fishing effort (shallow sets) across years (1994–2001).

For example, the highest net revenue per unit of effort occurs in February, while the highest loggerhead turtle interaction rate occurs in January. Thus, the trade-off (i.e., the number of sea turtle interactions for a given level of economic returns) varies by months.

In the first quarter (Jan.–Mar.), economic returns are high and loggerhead turtle interaction rates in those months are also high. In the second quarter (April–June), turtle interaction rates are at their lowest level, but economic returns are relatively high. Therefore, the trade-offs would be relatively low in the second quarter, compared to the first quarter. Prior to 2000 when the fishery was closed, the swordfish fishing efforts allocated were usually highest in the second and first quarters, 36% and 27%, respectively, compared to the third and fourth quarters (Fig. 2). However, after the fisheries reopened in 2005 with the cap in efforts allowed, most of the swordfish fishing efforts occurred in the first quarter. As shown, fishing in the first quarter results in higher net economic returns to the fishery, but the risk of exceeding sea turtle caps is also higher, compared to the other seasons.

Economic return and sea turtle interactions also varied by fishing location. Figure 3 shows the spatial variations in sea turtle interaction rates and economic returns. For example, in lower latitude areas (< lat. 28°N), the loggerhead sea turtle interaction rate is relatively low compared to economic returns. Thus, the expected trade-off (the number of sea turtle interactions for a given level of economic return) would be relatively small.

Both loggerhead sea turtle interaction rates and economic returns increase north of lat. 20°N up to lat. 32°N, with loggerhead sea turtle interaction rates increasing more steeply than economic returns. The peak of the loggerhead turtle interaction rate occurs in the area between lat. 33°N and lat. 34°N (Howell et al., 2008), while the economic return per unit of effort is highest in the area near lat. 32°N. As a result, the trade-off value would be relatively high in the area around lat. 33°N.

Trade-offs Before and After Regulations

The swordfish fishery reopened in 2004 with a set of regulations representing several years of effort by NMFS, the Western Pacific Fishery Management Council, the fishing industry, and conservation groups, to reduce the level of sea turtle interactions. The regulations, including mandatory use of circle hooks (replacing J hooks), use of fish bait (replacing squid as bait), and other conservation measures led to a dramatic reduction in rates of fishery interaction with loggerhead and other turtle species. However, the monthly patterns (peak and nadir) of the loggerhead turtle interaction rates were similar between the earlier period of the fishery (1994–2001) and the 2004–06 regulatory regimes, shown in our GAM analysis. This implies that the seasonality of sea turtle interactions with the fishery was unchanged although the overall inter-

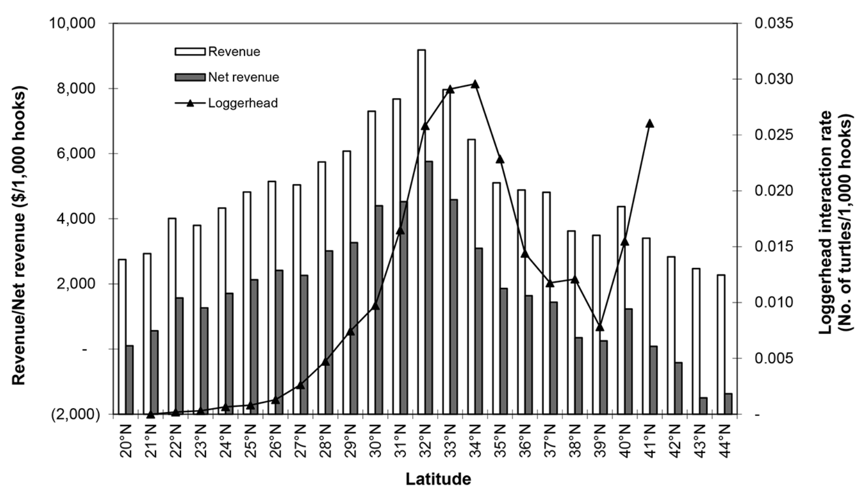

Figure 3.—Economic returns and loggerhead turtle interactions across latitudes.

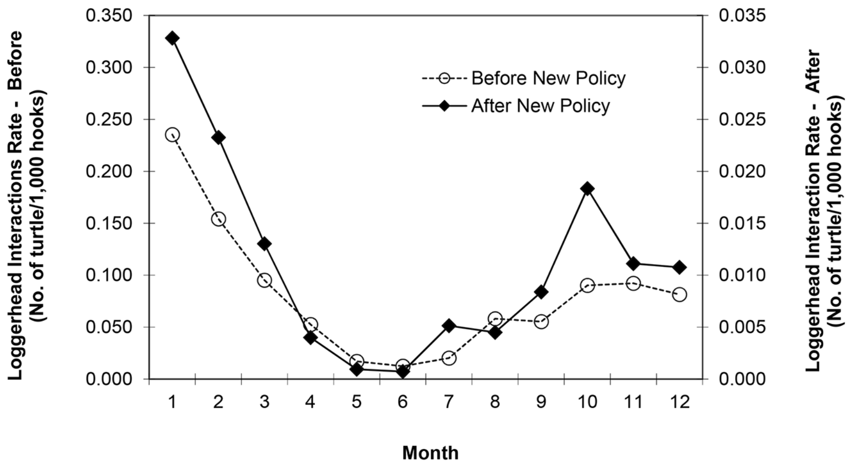

Figure 4.—Loggerhead interaction rates in the shallow-set swordfish longline fishery by month before (left y-axis) and after (right y-axis) new regulations were implemented in 2004 (note that left y-axis scale is 10× right y-axis scale).

action rate declined due to the new regulations.

Figure 4 illustrates the loggerhead interactions across months. For both before and after the new regulations, the loggerhead catch rate was the highest in the first quarter and lowest in the middle of the year (May, June, and July). However, the average monthly interaction rates of loggerhead turtles during 2004–06, 0.0111 per 1,000 hooks, were approximately eight times lower than the average monthly interaction rates from 1994 to 2001, 0.0804 per 1,000 hooks. Note that the scales of the two *y*-axes in Figure 4 are of much different magnitudes before and after the new policy regulations.

While sea turtle interactions declined, the catch rates of targeted fish species showed no significant changes under the new regulations. As a result, the magnitude of the trade-offs between loggerhead interactions and economic returns changed. During the 1994–2003 period, the swordfish fishery interacted with one loggerhead turtle for every 23,000 lb of swordfish caught, valued at $49,000 (nominal ex-vessel swordfish revenue). After the adoption of the new regulations on gear and bait (2004–06), the fishery interacted with one loggerhead turtle for every 238,000 lb of swordfish caught ($505,000 nominal ex-vessel swordfish revenue). Thus, under the lower interaction rate after the 2004 regulations, harvesting the same amount of swordfish may only interact with one-tenth of the sea turtle interactions that occurred in the period prior to the regulations.

On the other hand, to save one additional turtle (such as by imposing a more restricted sea turtle cap), it may cause ten times more foregone revenue of the swordfish fishery, since the marginal cost to the fishery for saving an additional sea turtle was much higher after the policy, when the sea turtle interaction rate was low.

Trade-offs and Fishermen's Behaviors

Fishing behavior in the swordfish fleet, such as fishing locations and fishing effort distribution among seasons, changes from year to year. Such changes can lead to substantial differences in the total number of sea turtle interactions, even at a fixed level of annual fishing effort. In the Hawaii swordfish longline fishery, if fishing effort is more concentrated in the first quarter, the risk of reaching the loggerhead sea turtle interaction cap is much higher than if fishing effort is more evenly distributed over the year.

For example, in 2006, the Hawaii-based longline swordfish fishery reached the cap of 17 loggerhead turtle captures within the first 3 months of the fishing season, with only 850 shallow sets. This led to a sudden closure of the fishery for the rest of that year. However in the prior year, 2005, the fishery caught only 12 loggerheads with 1,639 shallow sets, and the fishery remained open for the entire year. The number of fishing sets in the first quarter of 2006 was 55% higher than in 2005, which might directly contribute to more turtle interactions in 2006 since there was no significant difference in loggerhead turtle interaction rates between the first quarters of 2005 and 2006 (Gilman et al., 2006).

We predicted sea turtle interactions under several scenarios given a fixed fishing effort level but with different seasonal patterns. Historically, the seasonal patterns of the swordfish fishery have been rather variable. Different patterns of fishing effort can be assumed to reflect possible fishing behaviors of the fleet, and under each effort pattern the model can be used to predict the upper and lower bounds of sea turtle interaction with a specific fixed level of effort. Results of the model analysis could allow decision makers to evaluate the effectiveness of the fishing effort limits when no direct control is placed on the behavior of the fishermen (e.g., their seasonal fishing effort distribution).

Assuming an annual fishing effort limit of 2,120 shallow fishing sets and the loggerhead interaction cap of 17 turtles, this study evaluated various effort allocations across months (fishing behaviors) to estimate the impact on sea turtle takes and economic returns. The effort distributions studied included: 1) monthly allocation based on the historical (1994–2006) average pattern, and 2) the actual fishing effort pattern by month based on a particular year (e.g., 1994 or 2000). Results of the analysis are presented in Table 2.

The results indicate that fishing effort distributions across months lead to substantial differences in the trade-offs between sea turtle interactions

Table 2.—Predicted sea turtle interactions and economic returns under different fishing behaviors.

Fishing effort allocations[1]	Month	Monthly sets	Monthly cumulative sets	Cumulative loggerhead interactions	loggerhead net revenue[2] ($1,000)
Historical pattern (1994–2006 avg)	1	157	157	4	$595
	2	161	318	7	$1,290
	3	251	569	10	$2,102
	4	267	836	11	$2,733
	5	259	1,095	11	$3,056
	6	243	1,338	11	$3,614
	7	212	1,550	12	$3,970
	8	137	1,687	13	$4,072
	9	94	1,781	13	$4,184
	10	119	1,900	15	$4,254
	11	100	2,000	16	$4,384
	12	120	2,120	17	$4,548
1994	1	563	563	15	$2,132
	2	429	992	23	$3,985
	3	644	1,636	30	$6,070
	4	484	2,120	31	$7,212
2000	1	215	215	6	$814
	2	299	514	11	$2,106
	3	518	1,032	17	$3,782
	4	623	1,655	19	$5,253
	5	465	2,120	19	$5,833
2006 (actual)	1	284	284	5	$1,076
	2	327	611	8	$2,488
	3	328	939	17[3]	$3,550
	4	0	939	17	$3,550
	5	0	939	17	$3,550

[1]Allocations of monthly swordfish fishing effort follow the monthly pattern of shallow sets each year.
[2]Calculation of net revenue is based on monthly fishing effort (sets), and spatial and monthly net revenue (2005 values) per shallow fishing set from 1994 to 2006.
[3]The total loggerhead turtle catch reported here includes two unknown hardshell turtles. Data source: National Marine Fisheries Service (NMFS) Pacific Islands Region Observer Program.

and economic returns even though total fishing effort is constant. For example, if fishermen fished the same seasonal pattern as the historical average, their fishing effort would be fairly evenly distributed across the months with a slightly higher level in the second quarter and lower level in the first quarter. Under this scenario with an effort limit of 2,120 sets, the estimated number of loggerhead sea turtle interactions would be near 17 and the fleet-wide net revenue would be approximately $4.5 million. Applying the fishing effort distribution pattern observed in 2005, the model predicted the number of loggerhead sea turtle interactions as approximately 17 with an effort of 2,120 sets.[5]

In contrast, if fishermen behaved according to the 1994 monthly fishing effort pattern (with substantially more effort in the early months), the 2,120 effort limit would be exceeded in April. Given the concentration of fishing effort in these months, particularly in January, more interactions would be expected to occur, and the fishery probably would close early with sea turtle interactions reaching their limit (17 interactions) in February. Similarly, if fishermen followed the fishing effort pattern observed in 2000, the cap of sea turtle interactions would likely be reached by March. Therefore, if fishing effort is intensively applied during the first quarter, the risk of loggerhead sea turtle interactions reaching the cap would be high, with the result that shallow-set operations would be halted. For the remainder of the year, further longline fishing would be restricted to targeting tuna using deep-set gear. This situation actually occurred in 2006. During the first quarter of the year, fishing effort was highly concentrated and the accumulated number of loggerhead sea turtle interactions reached to 17 on 17 March 2006. As a result, the swordfish fishery was closed for the remainder of the year.

The model simulations and results discussed above illustrated the various trade-off relationships involved in fishery operations. Based on the information, we may design different policy options to search for an optimal solution for the two conflicting management goals.

[5]The actual number of sea turtle interactions in 2005 was 12, while total fishing effort was approximately 76% of its limit.

Policy Design and Implication

Previously, the lack of seasonal and area specific information on the trade-offs between sea turtle interactions and economic returns made it difficult to determine optimal time and area closures (WPRFMC, 2009). The model we developed in this study can be used to analyze the impacts of management policy options, including seasonal and spatial closures. In particular, the model can be used to examine swordfish fishing opportunities under various time-area closures, given the constraint of the sea turtle interaction cap. For example, we evaluated a trio of hypothetical area closures in which fishing was prohibited northward of lat. 32°N, 31°N, or 30°N. Figure 5 shows the results of these three hypothetical area closures and the baseline scenario (no area closure). In the analysis, we assumed that fishermen allocated their swordfish fishing effort in the first 4 months of the year, as in 1994 (Table 3 shows the monthly effort distribution) when the unit economic returns are high. Without any area closure, application of the entire 2,120 monthly cumulative sets was predicted to result in 31 interactions with loggerhead turtles and net revenue of $7.212 million.

However, given the interaction cap of 17 turtles, this alternative is not feasible; the swordfish fishery would be terminated in February after achieving a net return of less than $3.0 million, and the vessels would have to turn to tuna fishing using deep-set gear. Similarly, closure of the area north of lat. 32°N might reduce the number of turtle interactions by 3, but the risk of exceeding the cap would still be high; the expected number of interactions would be 28 loggerhead turtles and, given the cap, the fishery would likely be closed early in the year.

In contrast to these two scenarios, the closure of waters north of lat.

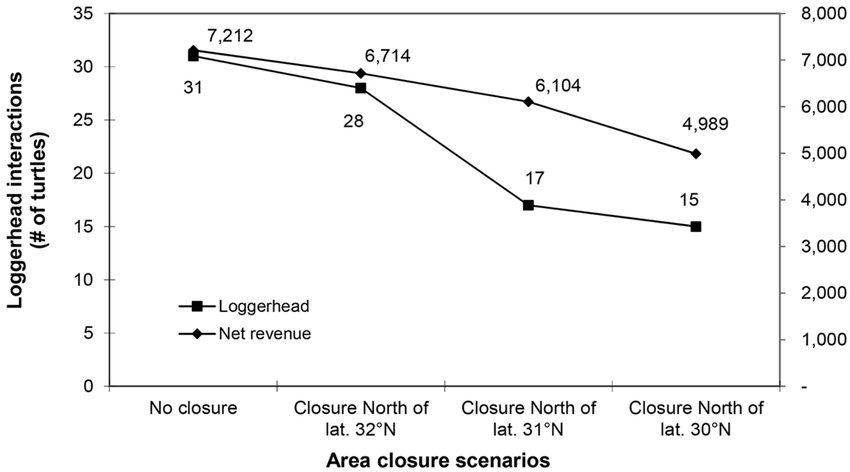

Figure 5.—Results of the hypothetical area closures and no area closure.

31°N would lead to many fewer turtle interactions. In this scenario, the predicted loggerhead interactions would not exceed the cap (17 loggerheads), and a net economic return of $6.104 million would be predicted, the highest net revenue the swordfish fleet could achieve, based on shallow-set operations, among the scenarios of area closure analysis presented in the graph (Fig. 5). From this area-closure-scenarios analyses, the average cost of reducing interactions of the swordfish fishery with sea turtles from 31 to 17 is $79,000 in net revenue ($101,000 in gross revenue) per sea turtle.

A previous study by Curtis and Hicks (2000) estimated the average cost of reducing interactions of the swordfish fishery with sea turtles before the new regulations was $41,262 per turtle. The figure estimated in this study was 2.5 times higher than the Curtis and Hicks (2000) report. Again, it shows that when the sea turtle interaction rate was lower, the average cost of further reducing interactions with sea turtles through partial area closure would be higher.

The limitation of swordfish fishing to waters south of lat. 31°N in this scenario corresponds roughly to similar advice given to fishermen to reduce interactions with loggerhead sea turtles by the NMFS TurtleWatch Program (Howell et al., 2008), which generates maps of sea surface temperature in the Hawaii longline swordfish fishing grounds and delineates areas where interactions with sea turtles are considered most likely to occur. The experimental maps are regularly posted online.[6]

Based on accumulated knowledge that loggerhead turtles prefer to stay in water colder than 65.5°F (about 18.5°C), the TurtleWatch maps delineate this boundary and advise longline fishermen to avoid fishing in waters colder than 65.5°F. During the first quarter of the year, the 65.5°F isotherm lies approximately along lat. 31°N. Thus if swordfish fishermen adhered to the TurtleWatch advice (effectively a voluntary area closure), the model predicts they would achieve $6.104 million net revenue while not exceeding the cap of 17 loggerhead sea turtle interactions.

In addition, results from the area-closure-scenarios shown in Figure 5 show that the cost of reducing interactions with sea turtles varied by the number of sea turtles that policy makers aim for as a limit. For example, if policy makers want to reduce the interaction with sea turtles from 31 to 15 (instead of the cap of 17 sea turtles in effect), the average cost would rise to $139,000 per turtle in net revenue ($156,000 in gross revenue), a 76% increase in cost to the fishery compared to the limit of 17 sea turtles. The unit cost increases dramatically if the policy makers aim for less than 15 sea turtle interactions.

Besides examining hypothetical area closures, the study evaluated the policy option of closing the swordfish fishery during months when high sea turtle interaction rates are expected. For example, a seasonal closure for the first 3 months could significantly reduce the risk of exceeding the sea turtle cap for the remainder of the year. Such a seasonal closure would limit fishing to months of lower sea turtle interaction rates and lower economic returns; however, it would extend the swordfish fishing season and allow the opportunity to fully use the fishing effort limit. Table 3 shows the results of a hypothetical seasonal closure in January. The single-month January closure may lead to a significant reduction in sea turtle interactions. Compared to the baseline scenario of no closure, the model predicted the number of loggerhead interactions could be reduced from 31 to 18, just slightly exceeding the cap.

The model demonstrated that there may be policy alternatives, either seasonal closures or area closures, that could have achieved higher economic returns than the actual industry performances in 2005 and 2006. Table 4

[6]http://www.pifsc.noaa.gov/eod/turtlewatch.php.

Table 3.—Predicted loggerhead sea turtle interactions and economic returns under a seasonal closure alternative.

Fishing effort allocation pattern	Month	Monthly sets	Monthly cumulative sets	Cumulative loggerhead interactions	Cumulative net revenue[1] ($1,000)
1994	1	0	0	0	$0
	2	429	429	8	$1,853
	3	644	1,073	15	$3,937
	4	743	1,816	17	$5,691
	5	304	2,120	18	$6,071

[1]Calculations of net revenue are based on monthly fishing effort (sets) and spatial and monthly revenues (2005 value) from swordfish fishing (effort unit measured by sets) from 1994 to 2006.

Table 4.—Predicted economic returns and number of loggerhead interactions under various scenarios and the actual economic returns of the industry in 2005 and 2006.

Scenarios or actual events	Fishing effort (sets)[1]	Loggerhead turtle interactions	Revenue ($ million)	Net revenue ($ million)
Actual industry performance				
2005	1,604	12	7.80	3.97
2006	939	17	5.86	3.55
Analysis alternatives				
1. Historical average (Table 2)	2,120	17	9.56	4.55
2. Seasonal closure (Table 3)	1,816	17	9.96	5.69
3. Area closure[2] (Fig. 5)	2,120	17	11.00	6.10
4. Area closure[3]	2,120	17	11.32	6.40

[1]The official PIFSC figure for shallow sets actually made in 2005 was 1,645 sets and in 2006 was 850 sets based on the landing data. The 1,604 and 939 figures in the table are PIRO's number of shallow sets made by vessels based on departure in 2005 and 2006, respectively. The study used the PIRO definition to count sets.
[2]North of lat. 31°N.
[3]East of long.166°W and north of lat. 31°N.

presents a summary of the estimated economic returns that might be realized from four hypothetical policy alternatives and the actual industry performances in 2005 and 2006. All four of the scenarios (three have been discussed above) result in a predicted net revenue (and gross revenue) higher than the estimated net revenue obtained by the industry in 2005 and 2006, while not exceeding the loggerhead sea turtle interaction cap (17 turtles).

As noted above, under an area closure north of lat. 31°N, the third scenario in Table 4, the industry might harvest $11 million worth of swordfish and earn approximately $6.104 million net revenue. If the closed area was reduced by closing only the area east of long. 166°W and north of lat. 31°N, as in the fourth scenario, the industry would be expected to achieve about $11.32 million revenue or $6.40 million net revenue. The predicted net revenue under this scenario is approximately $3 million higher than the net revenue in 2006 (although this calculation does not account for the revenue gained by these vessels as they fish for tuna with deep-set gear during the swordfish fishery closure for the rest of the year).

Conclusions

Conservation measures have resulted in a dramatic reduction of sea turtle interactions in the Hawaii-based longline fishery for swordfish. However, annual caps on loggerhead turtle interactions resulted in foregone fishing opportunity and created uncertainty for participants in the fishery owing to possible fishery closures.

This study explored the trade-offs between the risk of sea turtle interactions and the economic returns from swordfish fishing, and identified examples of alternative management options that could allow the swordfish fishery to operate throughout the year with a reduced risk of exceeding the cap on loggerhead sea turtle interactions. The study suggests that carefully designed area closures or seasonal closures confining fishing effort to areas and/or months with lower likelihood of interactions, would be one way to reduce the risk of the fishery reaching the sea turtle cap early in the fishing season and thus enable the industry to achieve higher annual economic returns. The study demonstrated that a bioeconomic model integrating information on fishery dynamics and net revenue can be a useful tool for fishery management decision making.

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