Fishing Opportunities under the Sea Turtle Interaction Caps—A Spatial Bio-economic Model for the Hawaii-based Longline Swordfish

Shichao Li and Minling Pan

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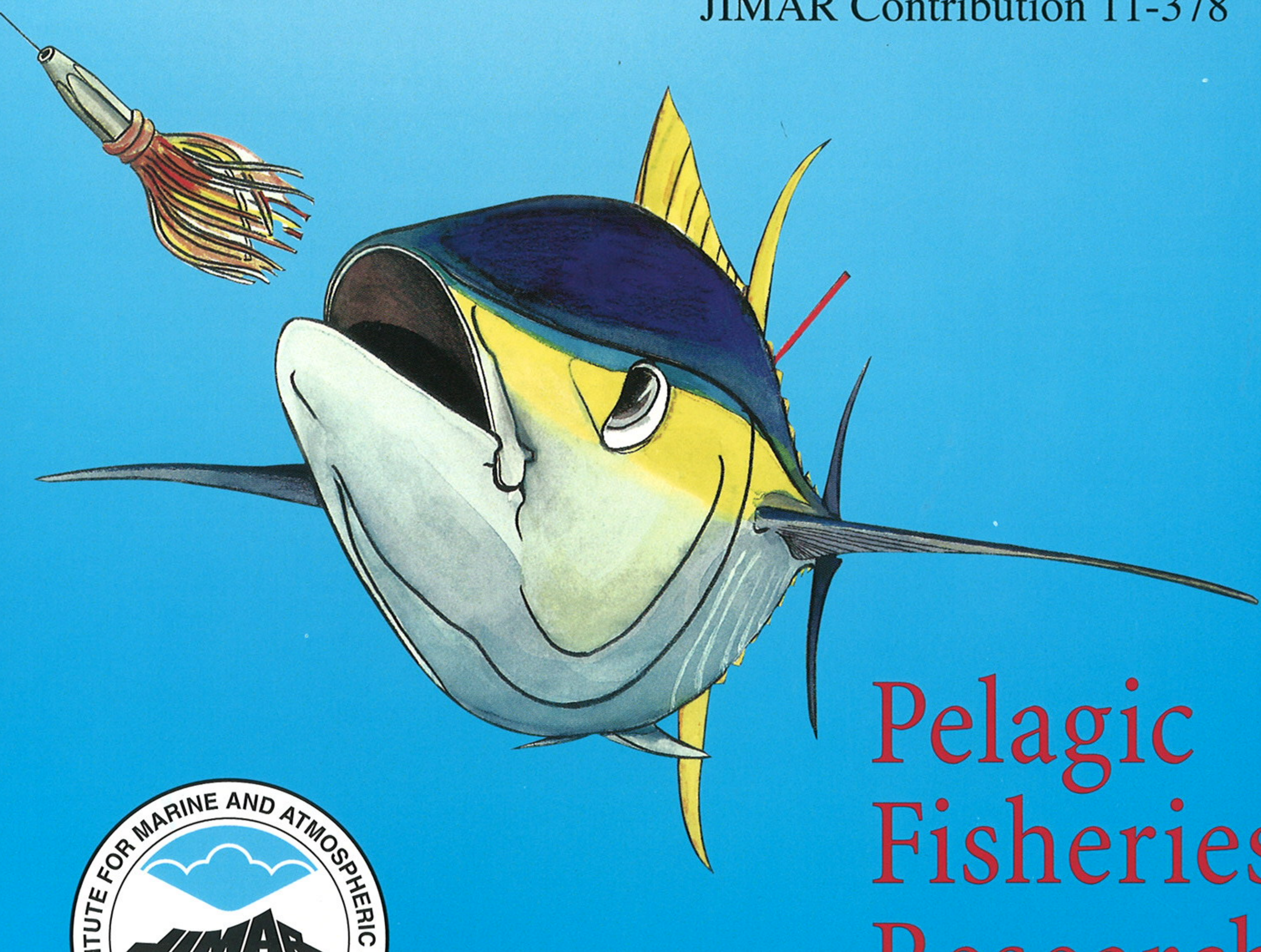

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Pelagic Fisheries Research Program

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Abstract

This study constructs a spatial bio-economic model to support decision-making processes for Hawaii-based longline swordfish fishery management. Generalized Additive Models (GAMs) are 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. Through simulation analyses of time-and-area closures, this research provides a tool for assessing the tradeoffs between reductions of sea turtle interactions and the resulting economic returns under different policy options, including the current mandated caps on sea turtle interactions. The model can be extended to explore potential modifications to the existing regulations for the Hawaii-based shallow-set pelagic longline fishery.

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1. RESEARCH BACKGROUND

Loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles have endured for millions of years, but they are listed as endangered and threatened, respectively, under the U.S. Endangered Species Act.[1] One source of mortality for sea turtle populations is incidental capture in pelagic longline fisheries (Watson *et al*. 2005; Lewison, Crowder and Freeman 2004; FAO 2004a, b; Hall 2003; Javitech Limited 2003). To reduce fishery impacts, the National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration, has established limits on the number of interactions allowed between fishing vessels and sea turtles and implemented strict fishery monitoring and Federal regulations to enforce the limits.[2] A sea turtle "interaction" is defined as an encounter between a turtle and a fishing vessel or gear, and usually implies that the turtle became entangled in a line or was caught on a hook (McCracken 2000). Fisheries with a risk of interacting with sea turtles and/or other sensitive species are subject to reduced economic opportunities unless they find ways to reduce such risks and keep their interactions within established limits. As a result of its sea turtle interactions, for example, the Hawaii-based longline swordfish fishery was temporarily closed in April 2001 (Kleiber 1998, 1999; McCracken 2000).

The fishery was reopened in April 2004 after NMFS adopted measures such as replacing J-shaped hooks with larger-size, circle-shaped hooks to reduce the risk of hooking and injuring sea turtles. Concurrently, other regulations were also enacted including the establishment of annual "caps" or limits on the allowable number of sea turtle interactions and a parallel limit on the number of shallow sets to restrict the amount of annual fleet-wide swordfish fishing effort. The latter is regulated through the issuance and use of transferable shallow-set certificates that are required for each fishing day in the Hawaii longline fishery for swordfish. The current caps of 17 loggerhead and 16 leatherback turtle interactions are based on the expected levels of interactions with the Hawaii-based longline swordfish fishery effort, with up to 2120 sets annually. Reaching any of these caps (loggerhead, leatherback or shallow sets) will result in closure of the swordfish fishery for the remainder of the calendar year (WPRFMC 2006).[3]

Although alterations in the fishing gear implemented in 2004 for the Hawaii-based longline fishery have significantly reduced sea turtle interactions (Gilman *et al.* 2006a), the Hawaii-based longline swordfish fishery continues to face a serious challenge in dealing with this problem. In 2005, the fishery did not reach the established sea turtle interaction caps and continued normal operations; however, in the first 3 months of the fishing season in 2006, the cap on loggerhead sea turtle interactions was reached and led to the immediate closure of the swordfish fishery for the remainder of the calendar year. As a result, the dock was suddenly congested with longline vessels attempting to sell their current loads of fish. This course of action flooded the market and deflated prices. Also, increased waiting times to unload fish resulted in a large number of fish of poor quality that were unsold. Swordfish longline boats had the option of continuing to fish using deep-set gear to target tuna.

Obviously, the swordfish fishery closures in 2001–2004 and 2006 led to negative economic impacts on the Hawaii-based longline fishery. For example, while swordfish

[1] http://www.nmfs.noaa.gov/pr/laws/esa/

[2] www.nmfs.noaa.gov/pr/species/turtles/regulations.htm

[3] The deep-set longline fishery for bigeye tuna does not face these restrictions.

landings reached 6.84 million pounds in 1999, they dropped dramatically (93%) to 0.485 million pounds in 2001; consequently, swordfish revenue, based on swordfish prices in 2001 ($2.39/lb), also declined 93% from approximately $16.35 million to $1.16 million (WPRFMC 2003). Similarly, the sudden closure of the swordfish fishery in 2006 reduced ex-vessel revenue for swordfish to $5.13 million, which was 20% of the historical high (1993) and 34% less than the 2005, based on nominal values (Ito and Machado 2001; WPRFMC 2006).

The Hawaii-based longline fishery is the largest U.S. domestic producer of swordfish in the Pacific.[4] In recent years, growing demand for swordfish has led to an increase of imports into domestic markets. Rausser *et al.* (2009) report an estimated annual market transfer effect of 1602 metric tons (MT) (3.5 million pounds) of additional U.S. swordfish imports when NMFS implemented the 2001 restriction on the Hawaii-based swordfish fishery. There are concerns that stringent regulations on the U.S. domestic pelagic longline swordfish fleet may result in an increase in swordfish fishing effort by foreign longline fleets, which are subject to less stringent controls on sea turtle interactions, and that could generate a negative impact on sea turtle populations (Bartram and Kaneko 2004; Sarmiento 2004; Kotas *et al.* 2004).

In response to a U.S. federal court order regarding sea turtle interactions in the Hawaii-based longline fishery (NMFS, 2001), Kobayashi and Polovina (2005) created a Generalized Additive Model (GAM) to predict interaction rates and provide a basis for analyzing time-area closures. The Western Pacific Regional Fishery Management Council (WPRFMC) has used this model to assess the effects of time-and-area closures on both the Hawaii-based longline fisheries (tuna and swordfish) and sea turtle interactions. The GAM predictions were used in a simulation analysis of various time-and-area closures on sea turtle interactions and the Hawaii-based longline fisheries. Appendix I lists features of the Kobayashi-Polovina (K-P) GAM.

However, the K-P GAM has several limitations.

1. The economic impact of alternative time-area closures on the fishery was solely represented by changes in revenue and did not include information on fishing costs. In reality, more distant fishing areas will have higher variable costs (transit time to and from the fishing grounds) and, therefore, result in changes in economic return (Hampton 2001).
2. The model offered single combinations of time-and-area closures in each scenario, and the estimate of reductions of sea turtle interaction from each closure was based on assumed fishing effort reallocations in which a complete spatial reallocation of lost fishing activity would occur, and a maximum of 1-month's fishing effort was to be reallocated symmetrically to adjacent months bounding the seasonal closure. These assumptions restricted monthly fishing effort allocations to a fixed pattern. Historically, the geographical and seasonal distribution of fishing effort varies considerably from month to month and from year to year. In turn, sea turtle interactions may vary substantially under the same season and/or area closure because of these changes in fishing behavior. Furthermore, a single combination of time and area closures has limits in its ability to meet the needs of fishery management as it does not allow for the assessment of multiple closure options.

[4] www.pifsc.noaa.gov/wpacfin/hi/dar/Pages/hi_fish_2.php

3. Sea turtle interaction rates in the Hawaii-based longline fisheries have changed from those assumed by Kobayashi and Polovina (2005) because of new fishing gear regulations implemented in 2004. The sea turtle interaction models for the Hawaii-based longline swordfish fishery need to reflect these changes.
4. There has been a change in the received wisdom and regulatory usage for the term “set type,” now delineated as either shallow sets (< 15 hooks per float) or deep sets (> 15 hooks per float). Previous model predictions based on three trip types, such as tuna, swordfish, and mixed, may not precisely reflect the actual sea turtle interaction rates associated with each trip type. The classification of trip type is subjective, sometimes based on reports from fishers and sometimes on the evaluation of NMFS staff that receive the data (Bigelow, Boggs and He 1999, p.181).
5. Annual sea turtle interaction caps and fishing effort limits require a new model to assess the number of sea turtle interactions by considering the effect of new fishing gear and the controls on fishing effort. The previous model examined alternative closure effects on percentage changes in sea turtle interactions and in ex-vessel revenue, based on historical fishing effort without application of a fishing effort limit.

This paper presents a modification of the K-P GAM to reestimate sea turtle interaction parameters and develops an economic simulation model to assist decision-making for Hawaii-based longline fishery management with respect to time-area allocation of fishing effort. The model allows managers to explore economic returns under constraints on fishing effort and sea turtle interactions.

2. OBJECTIVES

Based on the time-and-area-closure model constructed by Kobayashi and Polovina in 2001, this paper develops a spatial bio-economic model that combines a biological model of sea turtle interactions with a cost function for longline fishing. The four specific objectives of the study are as follows.

1. Predict sea turtle interactions in response to changes in the distribution of fishing effort and oceanographic conditions.
2. Incorporate a cost function into the model to enable analysis of revenue and net revenue under various fishery scenarios.
3. Design a multiple time-and-area-closure simulation model to assess the tradeoffs between economic returns and sea turtle interaction reductions.
4. Explore the conditions that allow for optimal fishing opportunities under the current caps on sea turtle interactions.

3. METHOD AND MODELS

3.1 Generalized Additive Models to Predict Sea Turtle Interactions

The incidental capture of sea turtles is a rare event. We assume that the total number of sea turtle interactions follows a Poisson distribution in which turtle interactions may occur in any longline fishing set (Cameron and Trivedi 1998; Pradhan and Leung 2006).

This paper applies GAMs under a family of Poisson distributions to predict loggerhead and leatherback turtle interactions with the Hawaii-based longline swordfish fishing gear at the mandated fishing sets level.

A GAM's smooth functions, or "smoothers," summarize the trend of a response measurement as a function of multiple predicators (Hastie and Tibshirani 1990). Several choices are available for smoother function specification in a GAM. We used smoothing splines because they generally perform better with regard to the bias-variance tradeoff than lowess or kernel smoothers (Kobayashi and Polovina 2005).

A GAM can be expressed as:

$$\log_e(\mu) = \Sigma\, S_j(X_j, d_j) \quad (j = 1 \text{ to } p)$$

where μ represents the conditional mean catch for the set of predicators ($x_1, x_2, \ldots, x_p$), S_j an unspecified smooth function, and d_j the degrees of freedom of the smoother. While the model is additive, the nonparametric form of the function S_j makes it flexible. As the degrees of freedom in a GAM increase, the function S_j gains more flexibility and becomes "rougher," which allows more hills and valleys or other complex shapes to be exhibited (Walsh *et al.* 2006).

The turtle-interaction GAMs in this paper were constructed using the software package *S-Plus,* version 6.2.1 running under Linux environment at the Pacific Islands Fisheries Science Center (PIFSC). Attributes representing the oceanographic environment, fishing practices, and gear characteristics were evaluated as predictors in the GAMs. By reference to the K-P model, these attributes include variables reported in the mandated federal logbooks, such as latitude, longitude, set type, number of hooks per float, day, month and year. Other variables, such as moon phase and satellite-measured sea surface temperature (SST) (weekly 0.1° latitude/longitude resolution, multichannel SST data collected by NOAA AVHRR polar-orbiting satellites and available from the University of Miami), were merged with the logbook data independently for this analysis using exact location and date to determine the corresponding values (Kobayashi and Polovina 2005). The GAMs for predicting loggerhead and leatherback turtle interactions were constructed from detailed observations gathered by the NMFS observer program, which monitored approximately 3–5% of the total longline fleet activity prior to 2001 and 100% of longline swordfish fishing since 2004. Hawaii longline observer data (n = 27,483 sets, with 22,368 deep sets and 5115 shallow sets) and Hawaii longline logbook data (n = 158,136 sets, with 122,395 deep sets and 35,741 shallow sets) from 1994 to 2006 were used. While the observer data were used to build the GAM model that estimated the sea turtle interaction rate, logbook data were applied to the GAM model to predict sea turtle interactions of the population (total fishing effort). The loggerhead and leatherback turtle interactions predicted by the GAMs for shallow sets were used for the Hawaii-based longline swordfish fishery.

To avoid the problem of trying to fit one parameter in each calendar month, we created a numerical variable by including daily variations with monthly changes. In other words, we used a smoothed continuous variable for the seasonal effect on sea turtle interactions rather than categorical variables for each month as in the K-P model (Sissenwine 2001). With reference to the K-P model, we also applied a rearward stepwise approach to identify those variables with a statistically significant contribution toward predicting sea turtle interactions. This stepwise procedure begins with a fully saturated model with all the variables specified with smoother functions. The model is simplified by eliminating insignificant variables or using linear functions instead of nonlinear smoother functions (Kobayashi and Polovina 2005). The Akaike Information Criterion, or AIC, (Akaike 1974) was used for the acceptance or rejection of terms in the GAMs. Degrees of freedom in each smoother function were constrained (e.g., df = 4 for seasonal effect, and df = 2 for other smoother functions) to eliminate extraneous curvature (Hastie and Tibshirani 1990; Kobayashi and Polovina 2005).

Based on the stepwise procedure and a reduction in AIC from 1,070.428 to 1,066.879, the final GAM for loggerhead turtle interactions included smoothed nonlinear effects of season ($p = 0.0072$), latitude ($p = 0.0030$), longitude ($p = 0.0068$), hooks per float ($p = 0.0073$), and sea surface temperature ($p < 0.0001$), a linear effect of moon phase, and a categorical effect of year. Each component of the loggerhead turtle interaction GAM is shown graphically in Figure 1. The plots depict the effects of individual predicators on the natural logarithm of loggerhead turtle interactions, and dashed lines represent twice-standard error bands. The leatherback turtle interaction function was estimated using the same procedure as the loggerhead turtle interaction function. The final GAM for leatherback turtle interactions included smoothed nonlinear effects of season, latitude, hooks per float, sea surface temperature and moon phase, and categorical effect of year.

These GAMs were applied to predict per-set interactions across all logbook data, using the selected predictor variables for loggerhead turtles and leatherback turtles. However, the discussion in the report focuses on loggerhead turtles because the loggerhead turtle interaction cap placed a tighter constraint on the fishery during the 2005-2006 period.

A randomization bootstrap procedure (Davison and Hinkley 1997) was applied to estimate 95% confidence intervals for monthly turtle interaction rates. In this procedure, individual longline sets in the observer database were randomly resampled with replacement to construct a new "bootstrap" database of the original size, and this process was repeated 1000 times (Gilman et al. 2006a).[5] The turtle GAMs were refitted to each new data set, and a new set of predicted turtle interactions was generated. Empirical 95% confidence intervals for monthly turtle interactions were estimated from the bootstrap distributions. The confidence intervals provide information about the uncertainty of predicted monthly interaction rates per unit of effort. On average, 95% of the time the mean of monthly turtle interaction rates predicted in this way will be inside these intervals. The results are shown in Figure 3. See Appendix I for the comparison between the K-P model's loggerhead turtle interaction GAM and the updated GAM.

[5] In the K-P model, each GAM was bootstrapped 100 times using random permutations of observer data (Kobayashi and Polovina 2005)

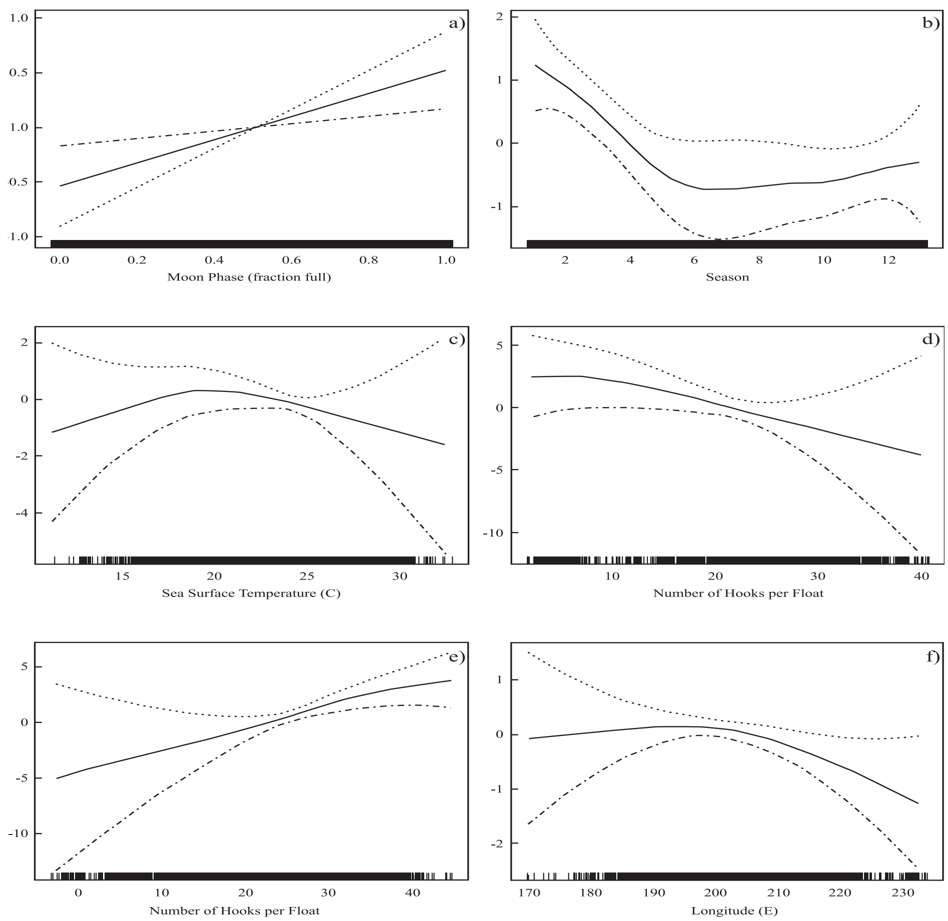


Figure 1. Effects of: a) moon phase; b) season; c) sea surface temperature; d) hooks per float; e) latitude; and f) longitude on loggerhead turtle interactions per set (all with twice-standard error bands).

3.2 Trip Costs and Contributing Factors

An assessment of the effects of time-area closures on economic returns must take into account fishing trip costs. Area closures may directly increase fishing cost through higher travel costs. One study suggested that an increase in travel time by 1 day per trip could generate an estimated net yearly loss of $4,000 to Hawaii-based longline fishers based on 10.8 trips per year. (Hamilton et al. 1996). The variable costs of Hawaii-based longline fishing trips include oil, bait, ice, gear, provisions, communications, certificates, and lightsticks. Based on unpublished 2005 cost-earnings survey data, we used a linear regression analysis to identify the statistically significant variables that contribute to the variable costs of Hawaii-based longline fishing. Prior to the regression analysis, the dependent variables were log-transformed to satisfy requirements of normality. After the data transformation, the value of kurtosis was reduced from 1.296 to - 0.028, and skewness was reduced from 1.395 to 0.281. Through the stepwise procedure by Statistical Package for Social Sciences (*SPSS* 12.0), the regression found that set type (targeting tuna or swordfish), fishing days, length of vessel, and the average distance from port to the location of fishing significantly affect trip costs (Table 1). The cost of each fishing trip was estimated from the regression model based on its set type, fishing days, vessel length, and average distance of sets to the port[6] recorded in the fishers' logbooks. Economic return in net revenue for each effort unit (set) was then calculated from ex-vessel revenue[7] by subtracting the variable costs.

Table 1. Regression model summary and coefficients of log-transformed trip cost

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

Number of observed trips = 181
Data source: 2005 cost-earnings survey data

3.3 Simulation Model Design

In this study, multiple time-area closures were designed based on different combinations of areas (by one degree of latitude and/or longitude) and seasons (1 to 12 month periods) to allow for the assessment of a variety of closure regimes. A seasonal closure could affect all fishing areas or apply to only a specific closure region. The model can simulate up to three independent area and seasonal closure alternatives simultaneously and, therefore, can generate a great number of seasonal and spatial closure scenarios. For example, from a single combination of time-and-area closure based on the historical effort pattern, 361,194 closure scenarios were generated in the simulation model developed by Kobayashi and Polovina (2001). The voluminous output from these exercises makes it difficult to select a clearly superior solution for a given optimization. Many scenarios should be evaluated together with additional input and criteria from fishers, industry and other concerned parties (Kobayashi and Polovina 2005, p. 6). Unfortunately, the debates on a large number of closure alternatives might paralyze the decision-making process, although attempting to avoid that problem was a major reason Kobayashi and Polovina created their efficiency frontier (NMFS 2006). In this paper, we narrowed down closure scenarios to those in which areas of high economic return overlap areas with high sea turtle interactions. The financial concept of "efficient frontier," used in Modern Portfolio Theory (Markowitz, 1952), was

[6] The distance from each set of a trip to the departure port was calculated by the locations (latitude and longitude) of the set and the port.

[7] The ex-vessel revenue of each set was calculated by multiplying the monthly average ex-vessel piece value for each species ($/fish), recorded at the United Fishing Agency auction in Honolulu, by the number of fish kept as recorded in Hawaii longline logbook data (unpublished data at the Pacific Islands Fisheries Science Center). Monthly ex-vessel piece values of 28 species from Hawaii longline logbook data were calculated based on 2005 Honolulu auction data (source: Pacific Islands Fisheries Science Center, unpublished data). This approach, while efficient with the available data, neglects differences in unit ex-vessel prices based on differences in fishing locations, individual vessels, fish size, etc. In future research, the ex-vessel revenue may be more precisely estimated if the fish value ($/piece) considers the variation in fishing locations, individual vessels, fish size, and other sources of variation.

applied to visualize tradeoffs between reward (economic returns in net revenue) and risk (sea turtle interactions) for different scenarios.[8]

The closure of fishing areas may force fishers to change their fishing behavior. The previous model (Kobayashi and Polovina 2005; NMFS 2006) was based on two scenarios:

- First, fishers expended the same amount of fishing effort in the open areas but fishing effort formerly spent in the closed area was not redistributed. The loss of fish catch, reduction of sea turtle interactions, and economic loss would be the maximum under this assumption.
- Second, effort in closed areas was redistributed to open areas. This would provide a minimal estimate of the possible economic impacts of the proposed closure, but with lower levels of sea turtle mitigation than if overall effort were reduced.

Considering variations in fishing locations and seasonality from year to year, we designed a simulation model to deal with flexible fishing effort allocations. Under the annual effort limit imposed on the fishery, fishing effort (number of sets) was allocated between zero and the maximum remaining for the year. Sea turtle interactions and fish catch were predicted under various scenarios of effort redistribution. The tradeoffs between sea turtle interaction reductions and economic returns resulting from various patterns of fishing effort were assessed to explore the effectiveness of closures.

We estimated sea turtle interaction rates during two time periods: 1994–2001, when fishers faced no restrictions on hook type or bait type; and 2004–2006, when regulations were imposed mandating use of circle hooks and mackerel-type bait. During the latter period, 100% longline observer coverage was also required The average number of hooks per shallow set for these two time periods was similar, 811 hooks during the first period and 820 hooks during the second. Sea turtle interaction rates, fish catch rates, and other quantities from the second period were applied in the simulation analyses of new policy options. The temporal and spatial variation in rates of loggerhead turtle interactions, swordfish catch, and net revenue returns are presented in Appendices II, III, and VI.

The simulation analyses employed different fishing effort patterns that reflect various assumptions in fishers' fishing behaviors. Monthly allocation of fishing effort either followed the empirical effort for each year or followed the average of monthly historical effort pattern from 1994 to 2006. In both cases, effort was restricted by the annual effort cap of 2120 shallow sets.

One simulation examined scenarios with the highest risk of sea turtle interactions. We assumed that fishers would fish at the beginning of a year, when sea turtle interactions and swordfish catches are both at their highest. In this case, historical maximum effort levels for January, February, and March were applied. Net revenue and the number of loggerhead and leatherback turtle interactions were selected as key variables to evaluate closure scenarios. The simulation results present information on cumulative turtle interactions and economic returns at the end of each month. The results would help managers:

- assess the number of sea turtle interactions;

[8] In the K-P model, the graph for "efficient frontier" displays percentage (per 5% bin) of sea turtle interaction reductions (e.g., leatherback turtles) on the *x*-axis, and percentage (per 5% bin) of fishing effort disruption on the *y*-axis (Kobayashi and Polovina 2005).

- determine when the caps would most likely be reached; and
- determine how many unused fishing certificates would remain under different assumptions about fishing behavior.

The flow diagram for the time-and area-closure simulation model is provided in Figure 2.

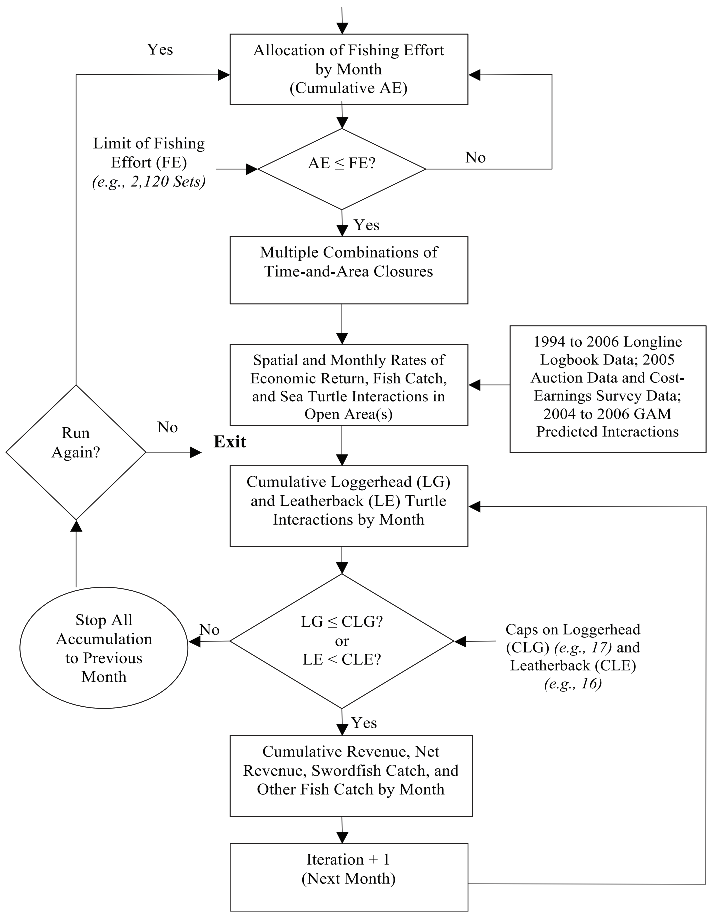


Figure 2. Flow diagram for the time-and-area-closure simulation model.

4. RESULTS AND DISCUSSION

The incidental catch of sea turtles in pelagic longline fisheries follows distinct spatial and temporal patterns (Witzell 1999). Since January 2007, the PIFSC Turtle Watch Program has been providing up-to-date information with maps illustrating the thermal habitat of loggerhead sea turtles in the Pacific Ocean north of the Hawaiian Islands.[9] According to a common view presented for Hawaii-based longline swordfish fishery management, seasonal overlap occurs between high economic return and a high number of sea turtle interactions. Based on observer data, research conducted by Gilman et al. (2006a) concludes that restricting fishing effort in the first quarter (January–March) would result in a significant reduction of sea turtle interactions, as well as a parallel loss in economic returns, because the value of swordfish is highest during that period. However, their analysis provided little

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

spatial information on the overlap of high economic return with sea turtle interactions. For example, an economic study by Pradhan and Leung (2006), which included fishing location, did not find that the degree of latitude of swordfish fishing had a significant effect on sea turtle interactions in Hawaii-based swordfish-targeted trips. The lack of spatial and temporal information on tradeoffs between sea turtle interactions and economic return increases the difficulty of determining optimal time-and-area closures (WPRFMC 2006). Our study could be the first to perform an analysis by examining both seasonal and spatial hot spots in sea turtle interactions and their associations with swordfish catch and economic returns.

This chapter presents the model results from the simulation analysis in two phases. First, this chapter presents the basic parameters of the model, which included the estimated number of sea turtle interactions and the spatial and temporal distribution of the sea turtle interactions under two different management regimes (in two different time periods). The results from the model also covered economic returns of fishing operations associated with the number of sea turtle interactions under these two different management regimes. Therefore, the information allowed us to examine the tradeoffs between sea turtle interactions and economic returns. The lack of spatial and temporal information on tradeoffs between sea turtle interactions and economic returns increases the difficulty of determining optimal time-and-area closures (WPRFMC 2006). Some studies (Witzell 1999, Pradhan and Leung 2006) have indicated the spatial and seasonal overlap between high economic returns and a high number of sea turtle interactions. However, there has been no study that allows tradeoffs between sea turtle interactions and economic returns in a specific area or time period. This study may be the first to examine both seasonal and spatial hot spots in sea turtle interactions and their associations with swordfish catch and economic returns.

In the second phase of this presentation, we discuss simulation results for several scenarios that represent different options of fisheries management policy.

4.1 Spatial and Temporal Patterns in Turtle Interactions, Swordfish Catch and Economic Return

Compared to the 1994–2001 period, the 2004–2006 period saw a dramatic decline in loggerhead and leatherback turtle interaction rates as the fishery reopened with new regulations on fishing gear (Figure 3). The average monthly interaction rates of loggerhead turtles were reduced from 0.08 per 1000 hooks to 0.01 per 1000 hooks). However, the monthly patterns of the peak and nadir in the turtle interaction rates were similar for these two periods. The loggerhead interaction rate is the highest in the first quarter (January to March), declines in the second and third quarters, but rises again in the fourth quarter. In other words, most interactions between loggerhead turtles and swordfish fishing occur in the winter season. For leatherback turtles, the interaction rate is highest in the fourth quarter (bottom of Figure 3). The seasonal pattern of loggerhead turtle interactions predicted in this study is consistent with the results of Gilman et al. (2006a), who analyzed virtually the same data. Their research also indicated that a large percentage of observed longline-loggerhead interactions occur in the first three months of the year, when Hawaii-based swordfish longline vessels are most active.

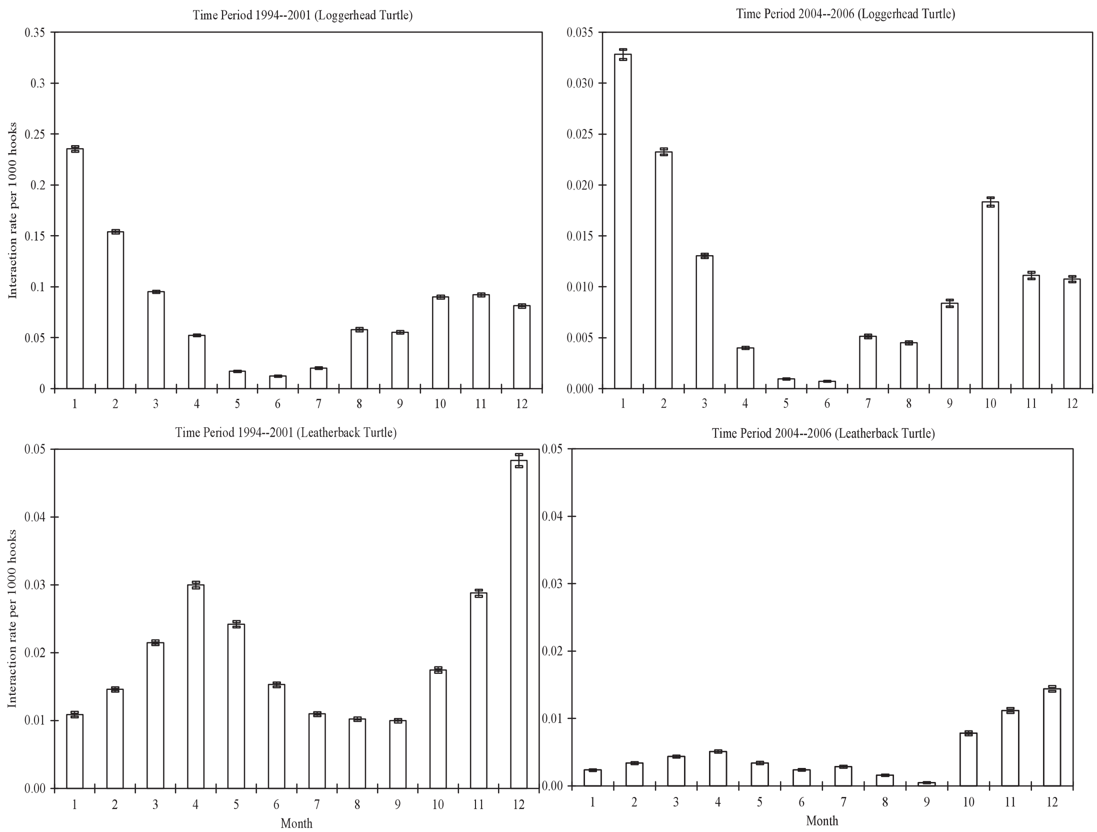


Figure 3. Monthly variations of predicted sea turtle interactions per 1000 hooks of shallow sets. Note: Error bars are bootstrapped (1000 times) 95% nonparametric confidence intervals and there is ten times difference in scale between the top panels (loggerhead turtles).

The swordfish fishery ground covers a large area in the central North Pacific. Figure 4 shows the spatial distribution of Hawaii swordfish fishing effort in 2005, the first full-year of fishing after the fishery was reopened. Research has found that loggerhead turtles in the central North Pacific travel westward, and move seasonally north and south primarily through the region at 28-40° N latitudes, corresponding to SST 15-25° C, (Polovina *et al.* 2004), and observer data show that this is where loggerhead interactions occur. Appendices IV and V present the estimated and observed interaction rates by latitude and longitude.

In both periods of observation, average loggerhead interaction rates were higher north of about 30° N latitude (Figure 5). However, the relationship between latitude and interaction rate for loggerheads differed between the two periods. In the first period of 1994–2001, the loggerhead turtle interaction rates generally increased with latitude north of 35° N, whereas during the 2004–2006 period they declined with latitude. This study did not examine what caused the differences.

The loggerhead turtle interaction rates and fishing efforts (hooks) showed similar patterns with longitude during the two periods (Figure 5). In general, the average loggerhead turtle interaction rates were higher in the eastern part of the fishing grounds. During the first period, loggerhead turtle interaction rates were relatively low between longitudes 152° W and 162° W, approximately, but in the second period of 2004-2006 this feature was not

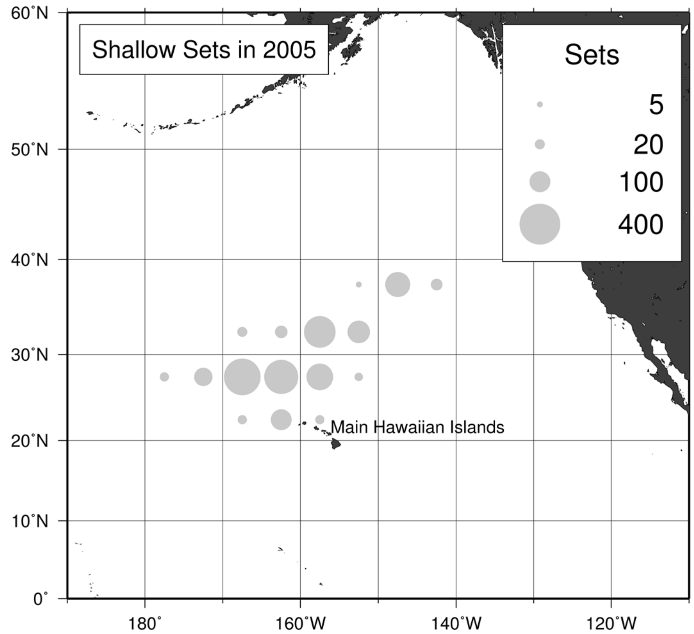


Figure 4. The spatial distribution of the Hawaii swordfish fishing effort in 2005.

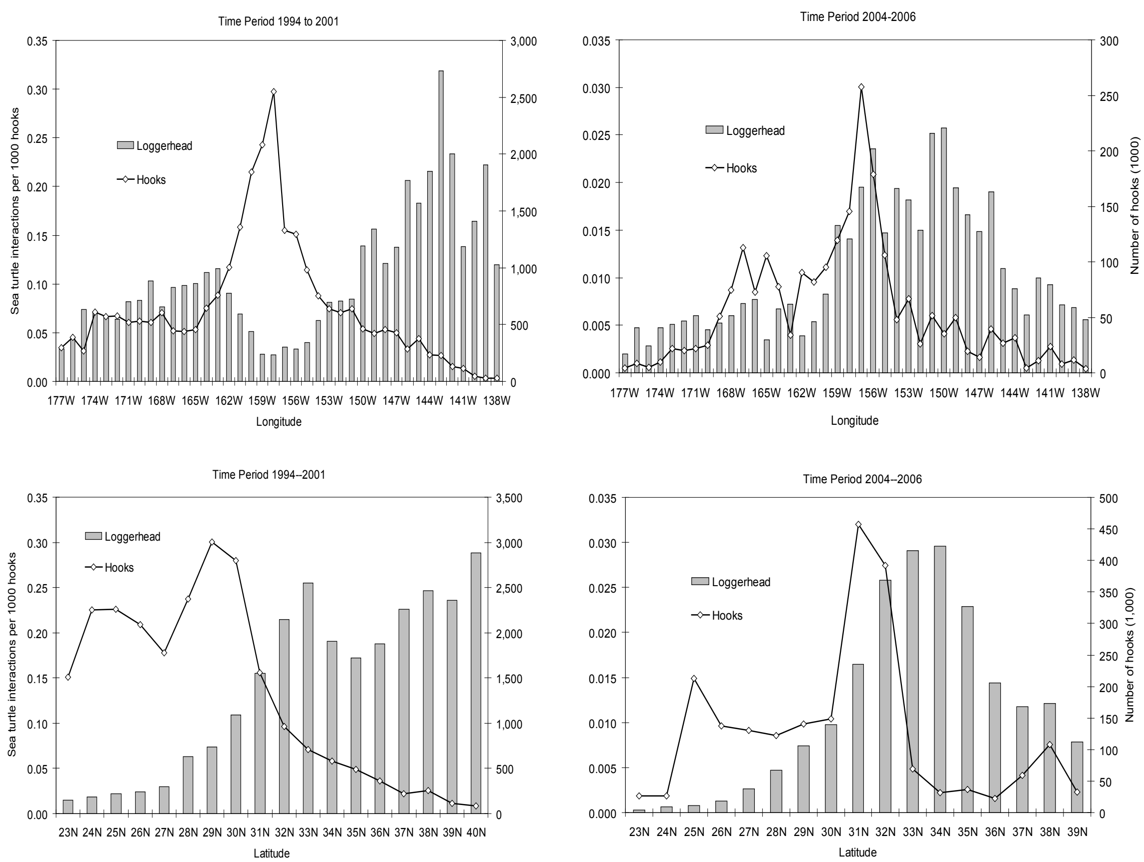


Figure 5. Predicted sea turtle interactions per 1000 hooks of shallow sets by latitude and longitude. Note: there is 10 times difference in scale between the left and right panels.

observed. Information on temporal and spatial variation in sea turtle interactions allows us to simulate the effects of time-and-area closures of the swordfish fishery on sea turtle interactions and economic returns.

Figure 6 shows economic return and swordfish CPUE (1000 hooks) in different months. The higher swordfish CPUE, and close proximity of fishing locations to departure ports (i.e., clustering around 30° N latitude), from January to March results in lower trip costs. Net revenues are highest in these months and the Hawaii-based swordfish longline vessels are most active in the first and/or second quarters. As a result, a greater percentage of net revenue for the swordfish fishery was identified from January to April (Figure 7). The first one-third of the year (January through April) accounts for nearly two-thirds (65%) of annual net revenues.

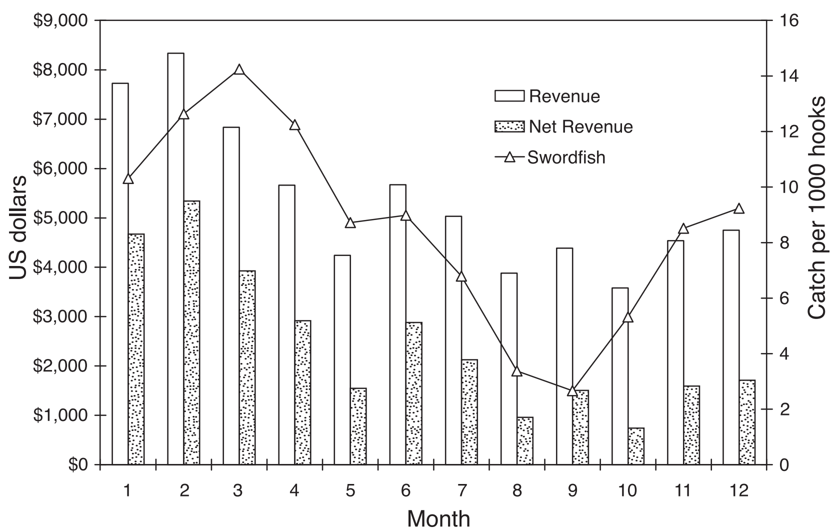


Figure 6. Monthly variation of economic returns and swordfish CPUE (1000 Hooks) of shallow sets (1994–2006).

The spatial pattern of swordfish catch and economic return from the swordfish fishery indicates that both the swordfish CPUE (15 fish/1000 hooks) and net revenue ($5800 in 2005 nominal value) are highest at about 32° N latitude.[10] The detailed figures are recorded in Appendix III. In contrast, average economic return and swordfish CPUE varied in a more complex way with longitude, but in general was highest east of 155° W and west of 165° W. Lower swordfish CPUE was located between 155° and 162° W longitude (see Appendix VI).[11]

[10] This research only applied monthly piece value of species to estimate revenues without considering the size differences by locations and vessels, which may affect the actual revenue. In future research, we will estimate revenue based on fish value ($/piece) at the trip level by month.

[11] We had personal communication with Dr. Christofer Boggs during the loggerhead turtle workshop held by the Western Pacific Regional Fishery Management Council on Dec. 19-20, 2007. He mentioned a very similar swordfish CPUE pattern by longitude for the Hawaii-based longline fishery from his previous research based on a 1991–1995 data set (Bigelow, Boggs and He 1999, p.188).

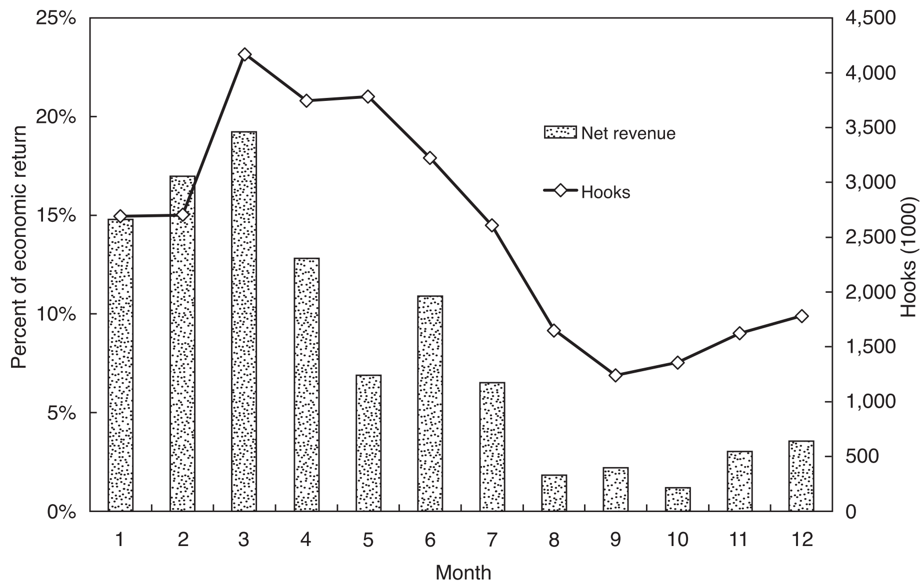


Figure 7. Monthly swordfish fishing effort and percentage of total economic returns (1994–2006).

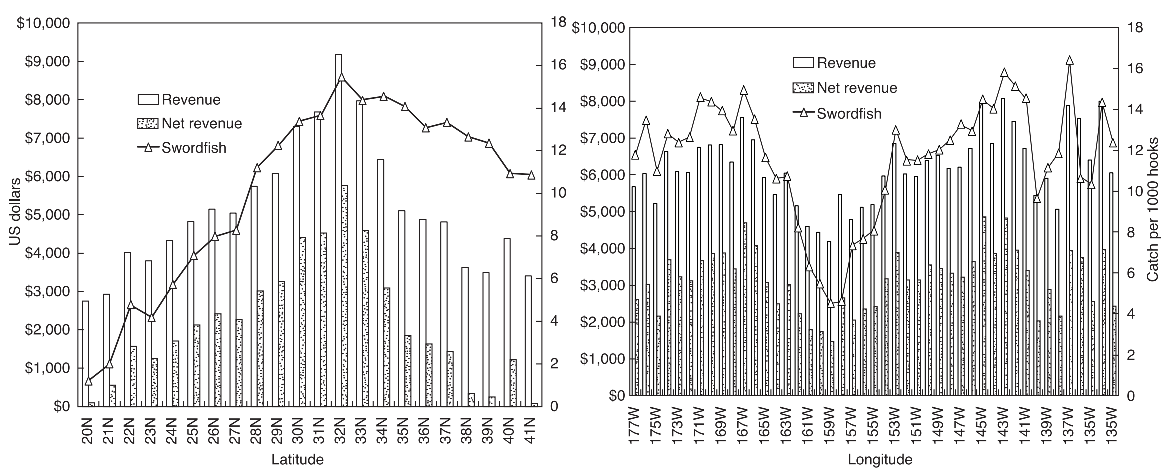


Figure 8. Economic return and swordfish CPUE (1000 hooks) of shallow sets by latitude and longitude (1994–2006).

The magnitude of sea turtle interactions depends on their relative abundance in the fishing areas and the season. Rather than using a static separation of data by month, latitude and longitude, the simulation model had a flexible design in terms of area (large or small, square or rectangle) and season (any combination of 1 to 12 months) to deal with dynamic spatial and temporal allocations. Sea turtle interactions, fish catch, and economic return per unit of effort in open areas were calculated from flexible area and seasonal combinations, so that these rates could be applied in assessing the effectiveness and economic viability of various closure scenarios.

4.2 Fishing Effort Pattern and Sea Turtle Interactions

Fishing effort distribution (spatial and temporal) has a profound impact on sea turtle interactions, and using a fixed, annual effort level with different distribution among months may result in different predicted sea turtle interactions. Fishing effort (shallow sets) from 1994 to 1998, for example, consistently operated with approximately 5000 fishing sets. The GAMs that were constructed from the sea turtle observer data indicate significant differences among these years in loggerhead turtle interactions (Figure 9).[12] One reason for the differences in annual sea turtle interactions could be the variations in monthly effort distribution and spatial distribution of fishing effort among years (Figure 10).

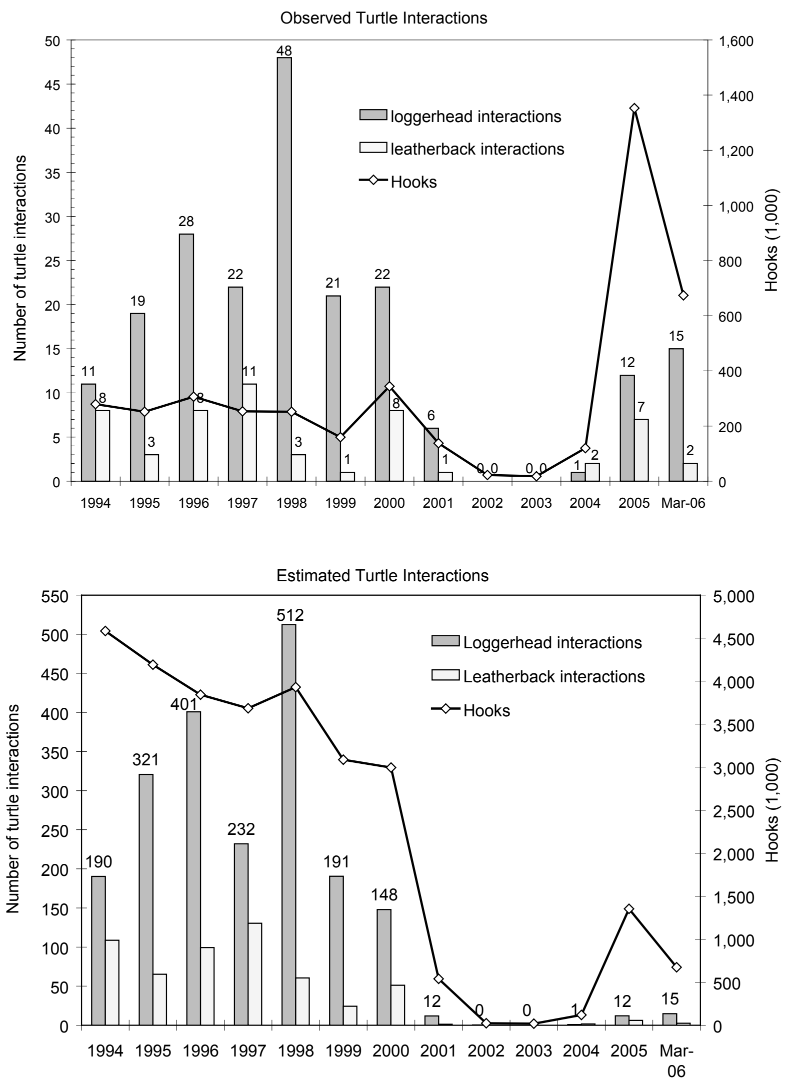


Figure 9. Observed and predicted sea turtle interactions from shallow sets.

[12] From 1994 to 2003, only a 5 to 20 percent coverage observer program was conducted in the Hawaii-based longline fisheries. Since 2004, a 100% coverage observer program has been implemented in the swordfish fishery.

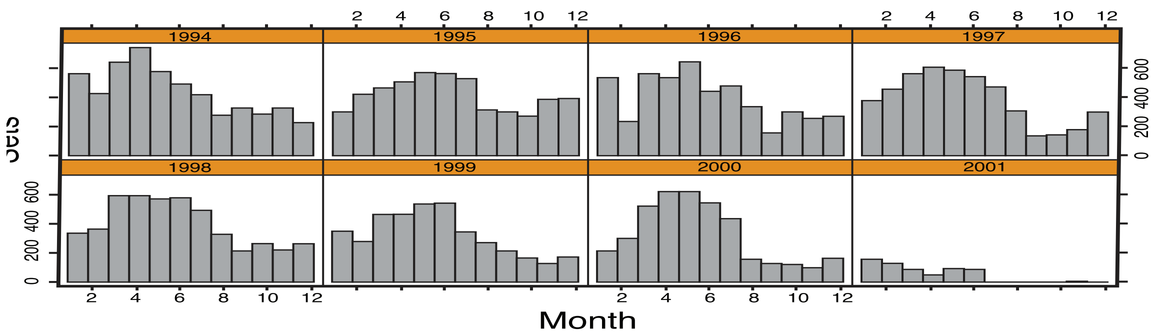


Figure 10. Monthly distribution of swordfish fishing effort (shallow sets) across years.

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, leading to a sudden closure of the fishery for that year. However, in the prior year, the fishery caught only 10 loggerheads with 1645 shallow sets, and the fishery remained open for the entire year. While there was no significant difference in loggerhead turtle interaction rates between the first quarters of 2005 and 2006 (Gilman *et al.* 2006b), the higher number of loggerhead captures during the first quarter of 2006 relative to 2005 resulted from the higher fishing effort which was mainly located north of 31° N latitude in 2006. The number of fishing sets in the first quarter of 2006, for example, was 55% higher than in 2005 (Table 2).

Table 2. Swordfish fishing effort and loggerhead turtle interactions in 2005 and 2006

Time period[a]		Number of swordfish sets			Loggerhead interactions	Loggerhead interaction rate	
		North 31°N (inclusive)	South of 31°N	Total		Per set	Per 1000 hooks
2005	January	58	2	60	1	0.0167	0.0209
	February	146	32	178	7	0.0393	0.0480
	March	85	225	310	1	0.0032	0.0038
	1st Quarter	**289**	**259**	**548**	**9**	**0.0164**	**0.0197**
2006	January	194	1	195	5	0.0256	0.0317
	February	265	62	327	3	0.0092	0.0119
	March	245	83	328	7	0.0213	0.0262
	1st Quarter	**704**	**146**	**850**	**15**[b]	**0.0176**	**0.0222**

[a] Time at beginning of set.
[b] In addition to the loggerhead turtles, observers recorded interactions with two hard-shell turtles of undetermined species.
Data source: National Marine Fisheries Service (NMFS) Observer Program.

4.3 Simulation Analysis under the Current Fishing Effort Limit

The application of our model as a tool in decision-making involves scenario or sensitivity analysis where policy options are analyzed as different scenarios or through variations in the underlying parameters (Pan, Leung, and Pooley 2000). To explore the efficient frontiers between loggerhead turtle interaction reductions and economic returns, we lifted the cap constraint on loggerhead turtle interactions in the simulation analysis. In the meantime, cumulative loggerhead turtle interactions by month were estimated for each scenario to predict when the cap would likely be reached. Five groups of analytical scenarios were simulated.

I. No area or seasonal closures
II. Seasonal area closures only—delaying the fishing season
III. Area closures only, by latitude and/or longitude
IV. Partial area closure combined with a seasonal closure
V. Multiple area and seasonal closures (e.g., two areas for two seasons)

As discussed in the section on simulation model design (Figure 2), the simulation analysis starts with monthly fishing effort allocation subject to the current annual effort limit (2120 shallow fishing sets). Under the bounded effort regulation, fishers have different alternatives to allocate their fishing effort among months. We assumed various allocations based on the historical effort distributions of the swordfish fishery: 1) the actual monthly effort from previous years; 2) annual historical distribution pattern by months; and 3) the highest fishing effort level in each month from 1994 to 2006. The purpose of applying various fishing effort patterns is to demonstrate the effect of fishing behavior on the tradeoffs between economic returns and loggerhead turtle interactions, rather than predicting fishing behavior for the Hawaii-based longline swordfish fishery.

For seasonal closures, the simulation analysis limits the fishing season. Zero effort is therefore allocated in January; or from January to February; or from January to March, accordingly, for each fishing effort pattern. For area closures, latitudinal closures (i.e., "no fishing north of …") or longitudinal closures (i.e., "no fishing east of …") in one-degree increments were simulated to generate independent efficient frontiers. Based on the efficient frontiers from latitudinal and longitudinal closures, partial area closures with seasonal closures from January to March were examined. Different scenarios were displayed graphically with the number of loggerhead turtle interactions on the *x*-axis, and net revenue returns on the *y*-axis. We then assess the selected seasonal and area closure scenarios based on the cap constraint of 17 loggerhead turtle interactions.

Scenario I. The Base Scenario — No Area or Seasonal Closures

We began by examining the effect of various fishing effort allocations on the tradeoff between sea turtle interactions and economic returns under the base scenario with no time or area closures. The tradeoffs from this scenario can be used as a baseline to be compared with the various time-and-area-closure scenarios. The simulation results indicated that under the actual monthly fishing effort pattern from 1994 to 2000 and no time or area closures, the number of loggerhead turtle interactions would reach the cap on loggerhead interactions before the limit of 2120 shallow sets were deployed.[13] In particular, if the monthly empirical effort or maximum monthly effort is applied just during the January–April prime period for swordfish fishing, the cap on loggerhead turtle interactions would be reached even before the end of February (Table 3a). For example, if swordfish fishing effort were distributed as in 1994, with 563 sets in January, 429 sets in February, 644 sets

[13] The results indicate that there are no cases of reaching the cap on leatherback turtle interactions; therefore, we focus on loggerhead turtle interactions.

in March, and 484 sets in April, then the total loggerhead turtle interactions would reach 31. By reference to this scenario analysis, the swordfish fishery season then would end in February under the regulation cap of 17 loggerhead turtle interactions. In other words, if fishing effort is intensively allocated from January to March, as it was in 1994, loggerhead turtle interactions will meet the cap before the end of the high swordfish fishing season is reached. As a result, the potential economic return from swordfish-targeted operations for the rest of the fishing season would be lost. Compared with fully using 2120 fishing certificates through April without closures ($7.2 million), the cost of closure from reaching the loggerhead turtle cap would be approximately $5.0 million (2005 nominal values) in terms of lost net revenue.

If fishers allocate their allowed fishing effort over the entire year following the 2005 pattern or the 1994–2000 historical allocation pattern (Table 3b), the fleet would have a low risk of reaching the cap for loggerhead turtle interactions but would also achieve lower economic returns (Table 3b). As a result of higher economic returns during the first 3 months, however, it is unlikely that fishing behavior will follow the historical apportioning pattern, particularly when the boats targeting swordfish have other economic options, like fishing for tuna, during other months. To maintain intensive fishing opportunities in the high fishing season that can result in greater economic return, area closures and/or seasonal closures could be one of the policy alternatives for fishery management.

Scenario II. Seasonal Area Closures—Postpone the Fishing Season

A seasonal area closure during periods of high potential for sea turtle interactions could help reduce interactions. Deferring swordfish fishing to later in the year may reduce sea turtle interactions and increase the likelihood that all shallow-set certificates can be used without exceeding the sea turtle caps. However, the fishers would be forced to fish during months with lower economic returns (Gilman *et al.* 2006a). The first quarter (from January to March) is the season with the highest fishing effort, the highest potential economic returns, and the highest number of sea turtle interactions. The simulation analysis examined the effect of deferring the fishing season to later months. When the fishing season starts in February instead of January, the level of loggerhead turtle interactions declines dramatically, coupled with an increase in fishing opportunities with greater economic return, compared to the scenario of no time or area closure (Table 4). Unfortunately, if the effort allocation followed the fishing pattern of 1994 or the monthly maximum effort, there would be a strong risk of reaching the loggerhead turtle interaction cap prior to using all fishing certificates, in addition to a loss of 1 month of the high fishing season. Starting the fishing season in March or April can also significantly reduce loggerhead turtle interactions, but would result in adverse economic impacts because the fishery would miss the highly profitable early months of the fishing season. The Hawaii-based longline swordfish fishery could suffer substantial negative economic returns from deferring the highly profitable fishing season. For example, compared to the base scenario fully using 2120 fishing certificates through April and no loggerhead turtle interactions, closure for the first month, the first 2 months, and the first 3 months would cost approximately $1.1 million, $2.3 million, and $3.1 million (2005 nominal values), respectively, in terms of net revenue loss, respectively (based on the 1994 fishing effort pattern for illustration). Of course, these analyses revealed the net revenue loss only with regard to fishing opportunities in the swordfish sector. Many

Table 3a. Predicted sea turtle interactions and economic returns under no closures (1994–2000 monthly actual effort distributions)

Fishing effort allocations[a]	Month	Monthly sets	Monthly cumulative sets	Cumulative loggerhead interactions	Cumulative leatherback interactions	Cumulative net revenue[b] ($1,000)
1994 pattern	1	563	563	15	1	$2,132
	2	429	992	23*	2	$3,985
	3	644	1,636	30	5	$6,070
	4	484	**2,120**	**31**	**7**	**$7,212**
1995 pattern	1	303	303	8	1	$1,148
	2	422	725	16	2	$2,970
	3	463	1,188	21*	3	$4,469
	4	511	1,699	23	6	$5,675
	5	421	**2,120**	**23**	**7**	**$6,201**
1996 pattern	1	534	534	14	1	$2,023
	2	235	769	19*	2	$3,038
	3	567	1,336	25	4	$4,873
	4	536	1,872	27	6	$6,138
	5	248	**2,120**	**27**	**7**	**$6,447**
1997 pattern	1	382	382	10	1	$1,447
	2	457	839	19*	2	$3,421
	3	562	1,401	25	4	$5,240
	4	608	2,009	27	7	$6,675
	5	111	**2,120**	**27**	**7**	**$6,813**
1998 pattern	1	338	338	9	1	$1,280
	2	361	699	16	2	$2,839
	3	595	1,294	22*	4	$4,765
	4	596	1890	24	6	$6,172
	5	230	**2,120**	**24**	**7**	**$6,459**
1999 pattern	1	352	352	9	1	$1,333
	2	279	631	15	1	$2,538
	3	466	1,097	20*	3	$4,047
	4	467	1,564	21	5	$5,149
	5	556	**2,120**	**22**	**7**	**$5,843**
2000 pattern	1	215	215	6	0	$814
	2	299	514	11	1	$2,106
	3	518	1,032	17	3	$3,782
	4	623	1,655	19*	6	$5,253
	5	465	**2,120**	**19**	**7**	**$5,833**
Monthly	1	563	563	15	1	$2,132
maximum	2	457	1,020	23*	2	$4,106
	3	644	1,644	30	5	$6,191
	4	456	**2,120**	**32**	**7**	**$7,267**

* The first month that exceeded 17 sea turtle interactions (the current cap).

[a]Allocations of swordfish fishing effort follow the monthly empirical effort of shallow sets for each year.

[b]The calculations of net revenue are based on monthly fishing sets, and spatial and monthly rates of net revenues (2005 nominal value) per shallow set from 1994 to 2006. See Section 3.2, "Trip costs and contributing factors" for economic returns.

Table 3b. Predicted Sea Turtle Interactions and Economic Returns under No Closures (2005 actual and the historical average effort distributions)

Fishing effort allocations[a]	Month	Monthly sets	Monthly cumulative sets	Cumulative loggerhead interactions	Cumulative leatherback interactions	Cumulative net revenue[b] ($1,000)
2005	1	78	78	2	0	$295
pattern	2	229	307	6	1	$1,285
	3	401	708	11	2	$2,582
	4	504	1,212	12	4	$3,772
	5	419	1,631	13	5	$4,295
	6	184	1,815	13	6	$4,718
	7	62	1,877	13	6	$4,822
	8	8	1,885	13	6	$4,828
	9	0	1,885	13	6	$4,828
	10	17	1,902	13	6	$4,838
	11	74	1,976	14	7	$4,934
	12	144	**2,120**	**15**	**8**	**$5,130**
Annual	1	157	157	4	0	$ 595
historical	2	161	318	7	1	$1,290
pattern	3	251	569	10	2	$2,102
	4	267	836	11	3	$2,733
	5	259	1,095	11	4	$3,056
	6	243	1,338	11	4	$3,614
	7	212	1,550	12	5	$3,970
	8	137	1,687	13	5	$4,072
	9	94	1,781	13	5	$4,184
	10	119	1,900	15	6	$4,254
	11	100	2,000	16	7	$4,384
	12	120	**2,120**	**17**	**8**	**$4,548**

[a]Allocations of swordfish fishing effort follow the monthly empirical effort of shallow sets for each year.
[b]The calculations of net revenue are based on monthly fishing sets and spatial and monthly rates of net revenues (2005 nominal value) per shallow set from 1994 to 2006. See Section 3.2, "Trip costs and contributing factors" for economic returns.

longline vessels actually switched to fish for tuna during the season independently of limits on fishing for swordfish.

Scenario III. Area Closures by Latitude and/or Longitude

Area closures created by one degree increments in latitude or longitude boundaries were examined to explore the efficient frontiers between loggerhead turtle interactions and net revenue returns. The simulation analysis found that a closure north of 32° N latitude would not be effective in reducing loggerhead turtle interactions. A closure north of 31° N latitude would be very effective in reducing interactions but would engender large declines in net revenue (Figure 11). An effective area closure that balances tradeoffs between reductions of sea turtle interactions and good economic returns is located between 30° N and 32° N latitude. For example, the net revenue from closure north of 31° N (using 1994 monthly fishing effort) would be $6.1 million, which is a loss of $1.1 million net

Table 4. Predicted Sea Turtle Interactions and Economic Returns under Seasonal Closures

Fishing effort allocations[a]	No closure		Fishing starts in February		Fishing starts in March		Fishing starts in April	
(2120 sets in the first four months)	**Logger-head (No.)**	**Net revenue**[2] ($1,000)	**Logger-head (No.)**	**Net revenue**[b] ($1,000)	**Logger-head (No.)**	**Net revenue** ($1,000)	**Logger-head (No.)**	**Net revenue** ($1,000)
1994 pattern	31	7,212	18	$6,071	10	$4,915	5	$4,122
1995 pattern	23	6,201	15	$5,589	8	$4,708	5	$4,009
1996 pattern	27	6,447	13	$5,240	9	$4,765	5	$3,903
1997 pattern	27	6,813	17	$5,843	9	$4,820	4	$4,057
1998 pattern	24	6,459	16	$5,601	9	$4,867	4	$4,074
1999 pattern	22	5,843	12	$5,338	8	$4,706	5	$3,764
2000 pattern	19	5,833	14	$5,349	8	$4,745	4	$4,052
Annual historical pattern	17	4,548	14	4270	12	3832	10	3341
Monthly maximum	32	7,267	18	$6,157	10	$4,849	4	$4,146
Average	**24**	**$6,117**	**16**	**$5,495**	**9**	**$4,690**	**5**	**$3,941**

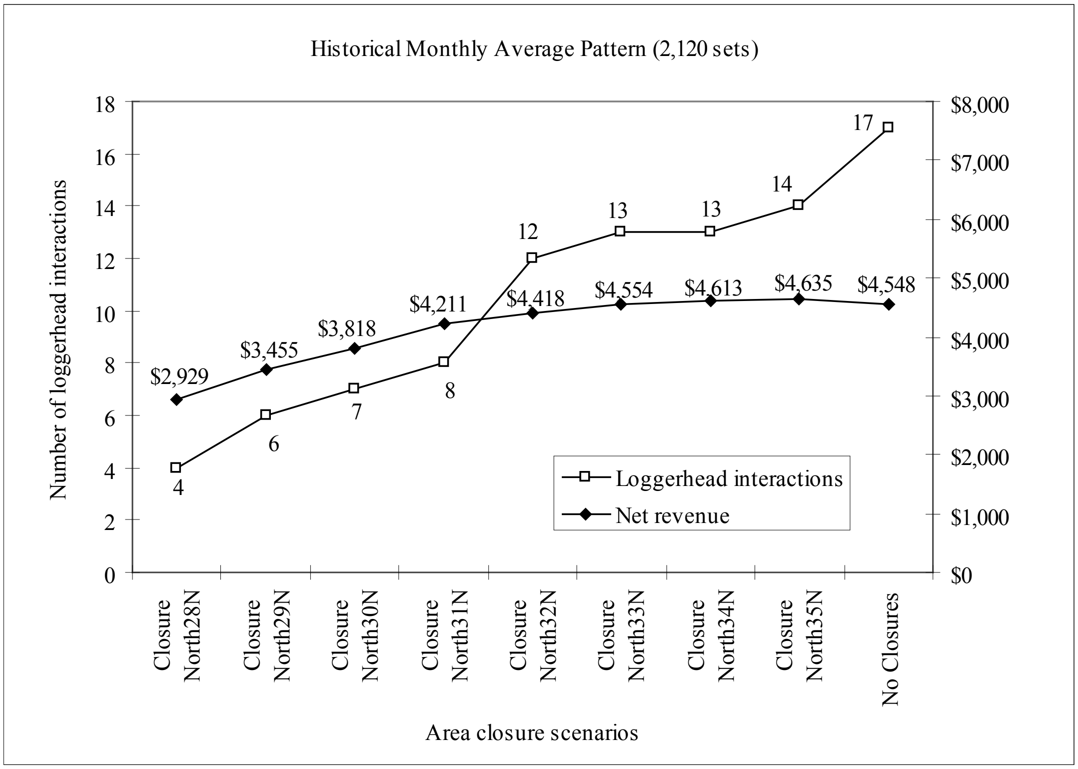
[a]Allocations of swordfish fishing effort follow the monthly empirical effort of shallow sets for each year.
[b]The calculations of net revenue are based on monthly fishing sets and spatial and monthly rates of net revenues (2005 nominal value) per shallow set. See Section 3.2, "Trip costs and contributing factors" for economic returns.

revenue from the 1994 baseline case of $7.2 million, while the number of loggerhead turtle interactions would decline from 31 to 17.

The simulation results indicate that area closures by longitude are more complicated than latitudinal closures. Assuming the 1994 monthly fishing effort pattern, a closure east of 160° W would reduce the number of loggerhead turtle interactions from 31 to 14, while increasing net revenue from $7.2 million to $8.5 million. However, the maximum net revenue return of $9.8 million occurs by implementing a closure east of 166° W longitude (Figure 12). It seems that fishing northwest (e.g., west of 160° W) and northeast (e.g., east of 145° W) of the Hawaiian Islands would result in higher net revenue returns (Figure 8 and Appendix VI). However, intensive swordfish fishing effort has historically been located in these zones, from 157° W to 160° W longitude (Figure 5). For example, approximately 77% of fishing effort was allocated north of the Hawaiian Islands between 145° W and 160° W longitude during the first quarters of 2005 and 2006. More research on the temporal and spatial behavior of the Hawaii-based swordfish longline fishery would be helpful. The new research could incorporate seasonal and spatial information on the value of swordfish, per piece, derived by integrating logbook data and market data from each longline trip.

Scenario IV. Partial Area Closure Combined with a Seasonal Closure

Considering the significant economic impact probably caused by even a brief seasonal closure as described in Scenario II, we examined the combination of area and seasonal closures. The first quarter was selected as the season to combine with an area closure over



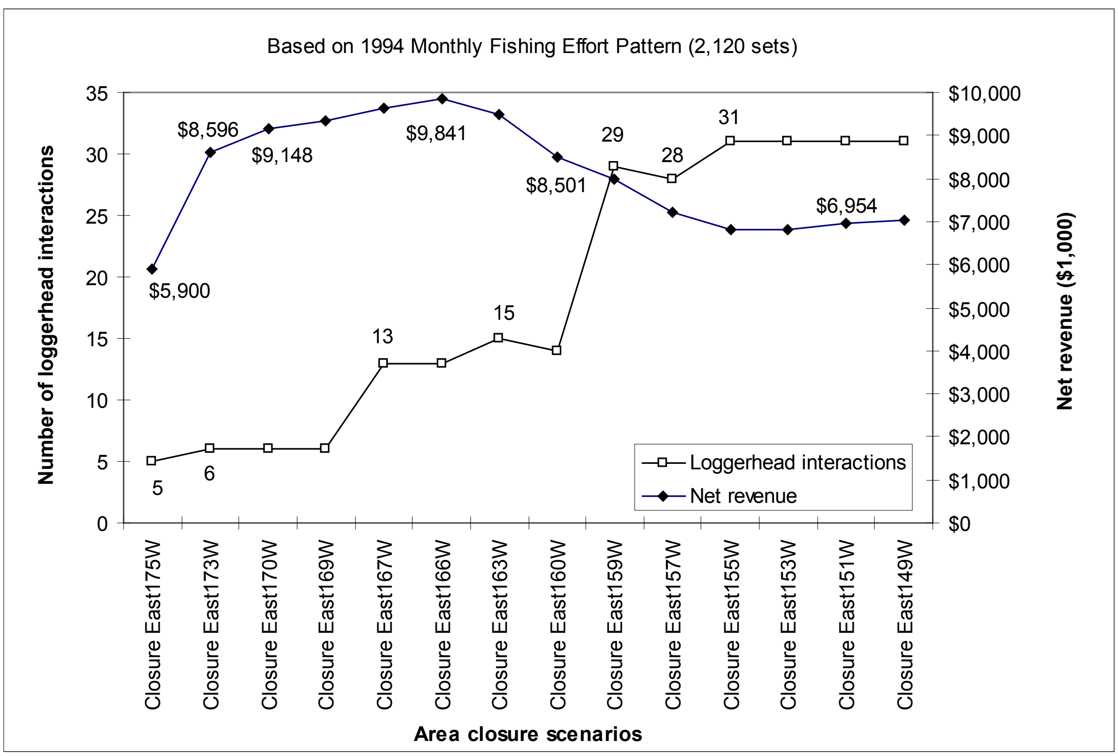


Figure 11. Tradeoffs between economic returns and sea turtle interactions under various area closure scenarios by longitude.

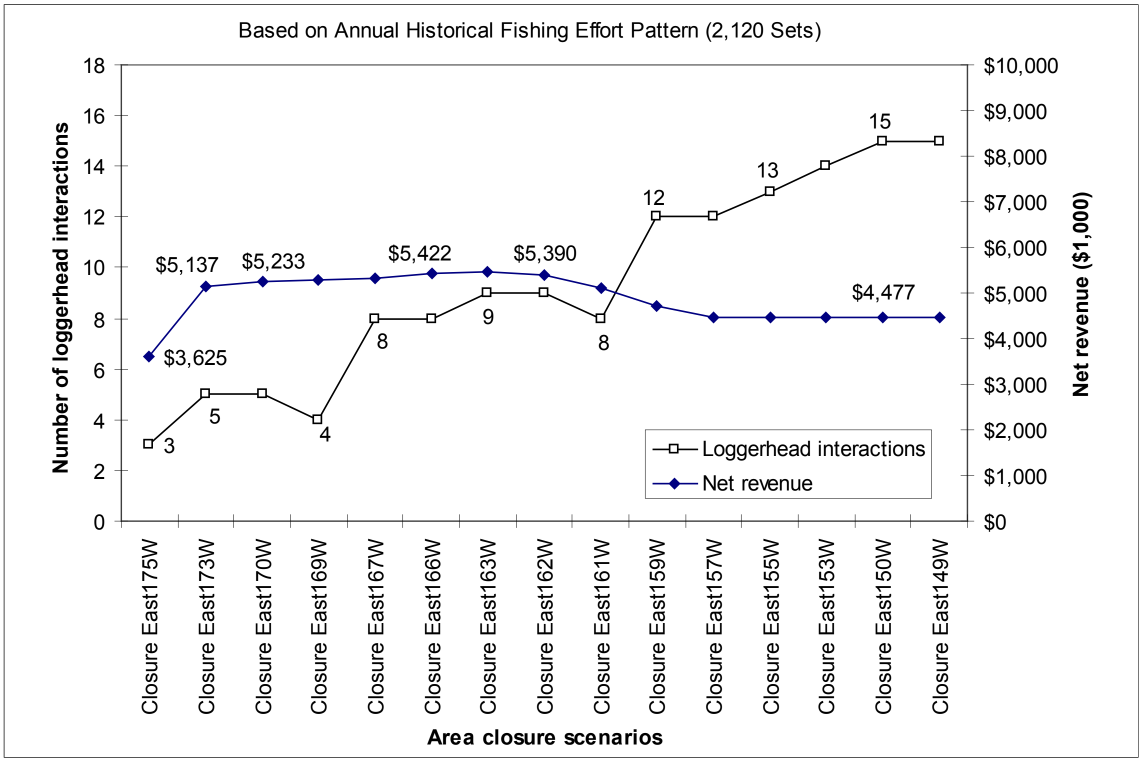


Figure 12. Tradeoffs between economic returns and sea turtle interactions under various area closure scenarios by latitude.

various degrees of latitude and longitude. Based on efficient frontiers from latitudinal and longitudinal closures, four scenarios were selected for partial area closures to be combined with a seasonal closure from January to March:

- closure north of 31° N
- closure north of 31° N and east of 160° W
- closure north of 31° N and east of 166° W
- closure north of 31° N and from 145 to 160° W

The simulation results across various fishing effort patterns (each totaling 2120 sets) indicate that closure north of 31° N and from 145 to 160° W is best able to reduce economic losses in net revenues (Table 5). Over all of the empirical effort patterns, except for 1994, the resulting level of loggerhead turtle interactions did not exceed the cap of 17. Under the current cap of loggerhead turtle interactions, greater economic returns across various fishing effort patterns could be achieved by reducing or raising the annual fishing effort limit under a partial seasonal area closure.

Table 5. Predicted Sea Turtle Interactions and Economic Returns under Various Patterns

Fishing effort allocations[a] (2120 sets)	Closure north of 31° N (Jan–Mar)		Closure north of 31° N and east of 166° W (Jan–Mar)		Closure north of 31° N and east of 160° W (Jan–Mar)		Closure north of 31°N from 145-160° W (Jan–Mar)	
	Logger-head	Net revenue ($1,000)	Logger-head	Net revenue ($1,000)	Logger-head	Net revenue ($1,000)	Logger-head	Net revenue[b] ($1,000)
1994 pattern	17	$6,104	17	$6,396	18	$6,626	18	$6,829
1995 pattern	14	$5,444	14	$5,675	15	$5,807	15	$5,925
1996 pattern	14	$5,538	14	$5,765	14	$5,967	14	$6,150
1997 pattern	16	$5,921	16	$6,186	17	$6,349	17	$6,494
1998 pattern	15	$5,701	15	$5,932	15	$6,075	15	$6,200
1999 pattern	13	$5,139	13	$5,332	13	$5,477	13	$5,603
2000 pattern	13	$5,289	13	$5,473	13	$5,568	13	$5,649
Monthly Maximum	18	$6,136	18	$6,437	18	$6,668	18	$6,872
Average	**15**	**$5,659**	**15**	**$5,900**	**15**	**$6,067**	**15**	**$6,215**

[a]Allocations of swordfish fishing effort follow the monthly empirical effort of shallow sets for each year.
[b]The calculations of net revenue are based on monthly fishing sets, and spatial and monthly rates of net revenues (2005 nominal value) per shallow set. See Section 3.2, "Trip costs and contributing factors."

Ignoring the current loggerhead turtle interaction cap and assuming the 1994 effort pattern, we examined the tradeoffs between loggerhead turtle interactions and net revenue returns across various closure scenarios under the 2120 fishing effort limit (Figure 13). We also assessed economic losses and loss of fishing opportunities that would result from reaching the cap of 17 loggerhead turtle interactions under the 1994 fishing effort pattern. The results indicate that a closure north of 31° N and from 145 to 160° W (Scenario 7 in Figure 13) during the first quarter are more effective than a seasonal closure of all fishing areas, and other partial seasonal area closures, in achieving favorable economic returns in net revenue under the cap of 17 loggerhead turtle interactions (Table 6).

A closure north of 31° N latitude from January to March is consistent with the advice from the Pacific Islands Fisheries Science Center (PIFSC) Turtle Watch Program, which suggested that fishers avoid fishing in waters colder than 65.5° F (18.5° C); SST is negatively correlated with the degree of latitude. Based on the Turtle Watch Program, the 65.5° F surface isotherm is located approximately between 30° and 31° N latitude during the first quarter in the Hawaii-based longline fishing area, although sea surface temperature distributions may vary from month to month and year to year.

Scenario V. Multiple Area and Seasonal Closures (e.g., two areas for two seasons)

The simulation model can analyze the risk of loggerhead turtle interactions in the situation where fishers may only fish in the first and last 3 months of a year when swordfish CPUE is usually high. Fishers may use their shallow-set fishing certificates (2120 sets) exclusively or mostly in the first quarter (January to March) and fourth quarter (October to December) without fishing in the summer season. Simulations based on the historical effort pattern from October to March, indicate that multiple partial closures could be more effective in reducing loggerhead turtle interactions while achieving good economic returns. For example, a combination of a closure north of 31° N latitude from 145-160° W longitude

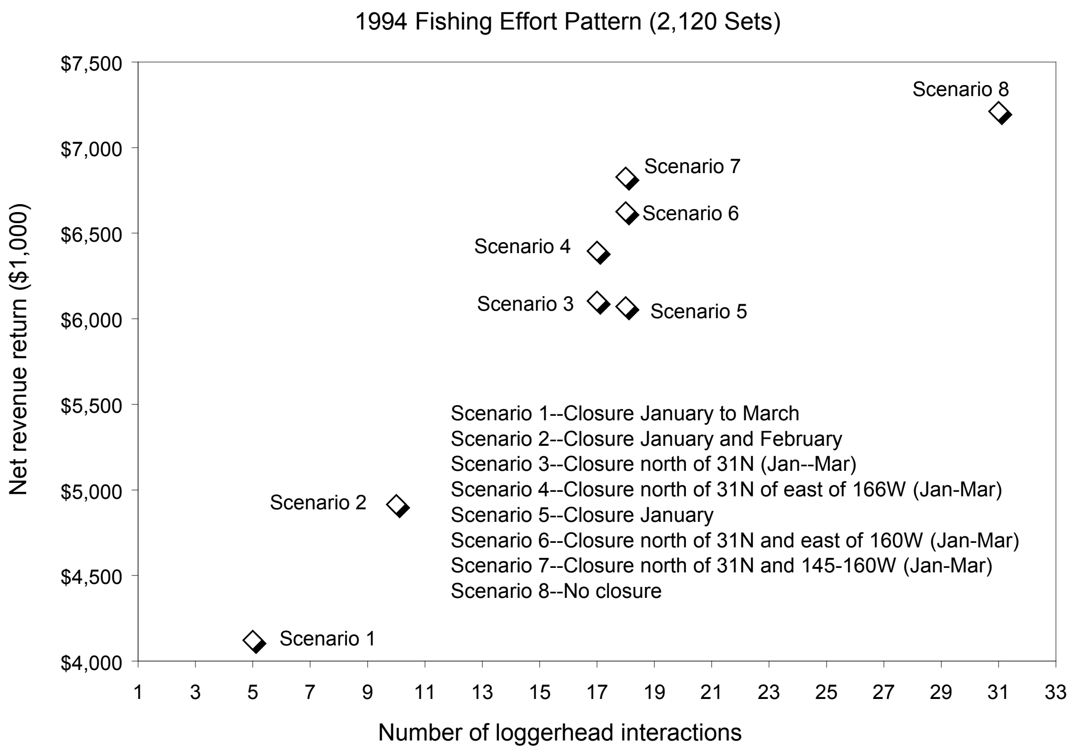


Figure 13. Tradeoff between loggerhead turtle interactions and economic returns across various scenarios.

for the first quarter, along with a closure north of 35° N latitude for the fourth quarter, would avoid reaching the cap of loggerhead turtle interactions while producing a net revenue of approximately $5.6 million. Without this second partial seasonal area closure, the simulation analysis indicates a risk of exceeding the loggerhead turtle interaction cap in October as seen in Figure 14. The economic returns in net revenue would be lower if the fishery closed in October without using up the effort quota; the fishery would receive only $4.8 million in net revenue. The top panel of Figure 14 presents total economic return and loggerhead turtle interactions across different scenarios based on an October to March fishing season with the effort pattern indicated in the bottom panel. The bottom panel provides monthly loggerhead turtle interactions from the single and selected multiple closures, and economic returns from single and multiple closures are displayed in the top chart.

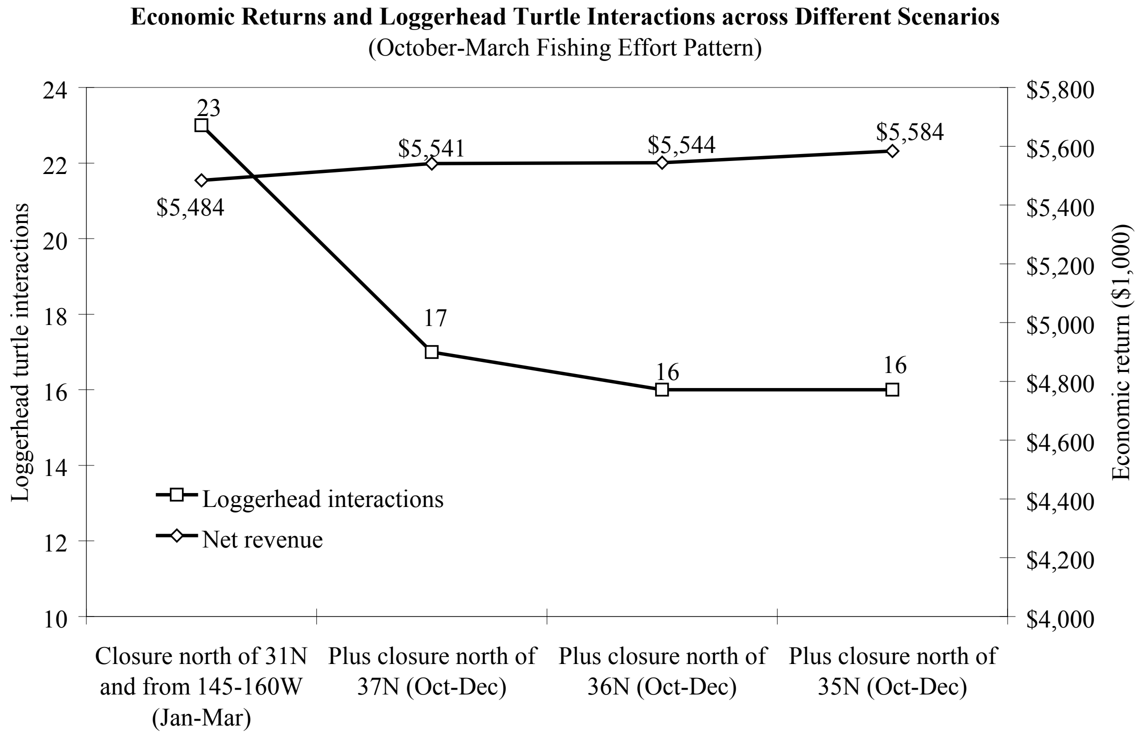
5. CONCLUSION

Despite recent gear modifications and regulatory measures to reduce the likelihood of longline interactions with sea turtles, there is still a risk that the Hawaii swordfish longline fishery will reach the annual sea turtle interaction caps imposed on the fleet. This study constructed a bio-economic model enabling fishery managers to consider a variety of policy options to reduce the risk of sea turtle interactions through area and seasonal closures. The model allows the analysis of tradeoffs between economic returns and sea turtle interaction reductions under different levels of fishing effort limits (higher or lower than 2120 sets) and different fishing behaviors (e.g., translocation of fishing effort). It also can predict

Table 6. Constraint of the Loggerhead Turtle Interaction Cap on Various Scenarios

Scenarios	Month	Monthly sets[1]	Cumulative sets	Cumulative loggerhead interactions	Cumulative revenue[b] ($1,000)	Cumulative net revenue[b] ($1,000)
No time-and-area closure scenario	1	563	563	15	$3,549	$2,132
	2	120	**683**	**17**	**$4,364**	**$2,651**
Closure in January	1	0	0	0	0	0
	2	429	429	8	$2,912	$1,853
	3	644	1,073	15	$6,547	$3,937
	4	743	**1,816**	**17**	**$9,959**	**$5,691**
Closure north of 31° N (Jan-Mar)	1	563	563	4	$2,723	$1,400
	2	429	992	10	$5,237	$2,903
	3	644	1,636	16	$8,778	$4,961
	4	484	**2,120**	**17**	**$11,000**	**$6,104**
Closure north of 31° N and east of 166° W (Jan-Mar)	1	563	563	4	$2,814	$1,485
	2	429	992	10	$5,472	$3,124
	3	644	1,636	16	$9,094	$5,254
	4	484	**2,120**	**17**	**$11,317**	**$6,396**
Closure north of 31° N and east of 160° W (Jan-Mar)	1	563	563	4	$3,032	$1,695
	2	429	992	10	$5,709	$3,352
	3	644	1636	16	$9,341	$5,484
	4	300	**1936**	**17**	**$10,719**	**$6,192**
Closure north of 31° N from 145-160° W (Jan-Mar)	1	563	563	4	$3,257	$1,883
	2	429	992	10	$5,959	$3,565
	3	644	1636	16	$9,580	$5,686
	4	300	**1936**	**17**	**$10,957**	**$6,394**

[a]Allocations of swordfish fishing effort follow the monthly empirical effort for 1994.
[b]The calculations of economic returns are based on monthly fishing sets, and spatial and monthly rates of economic returns (2005 nominal value) per shallow set. See Section 3.2, "Trip costs and contributing factors", for economic returns.



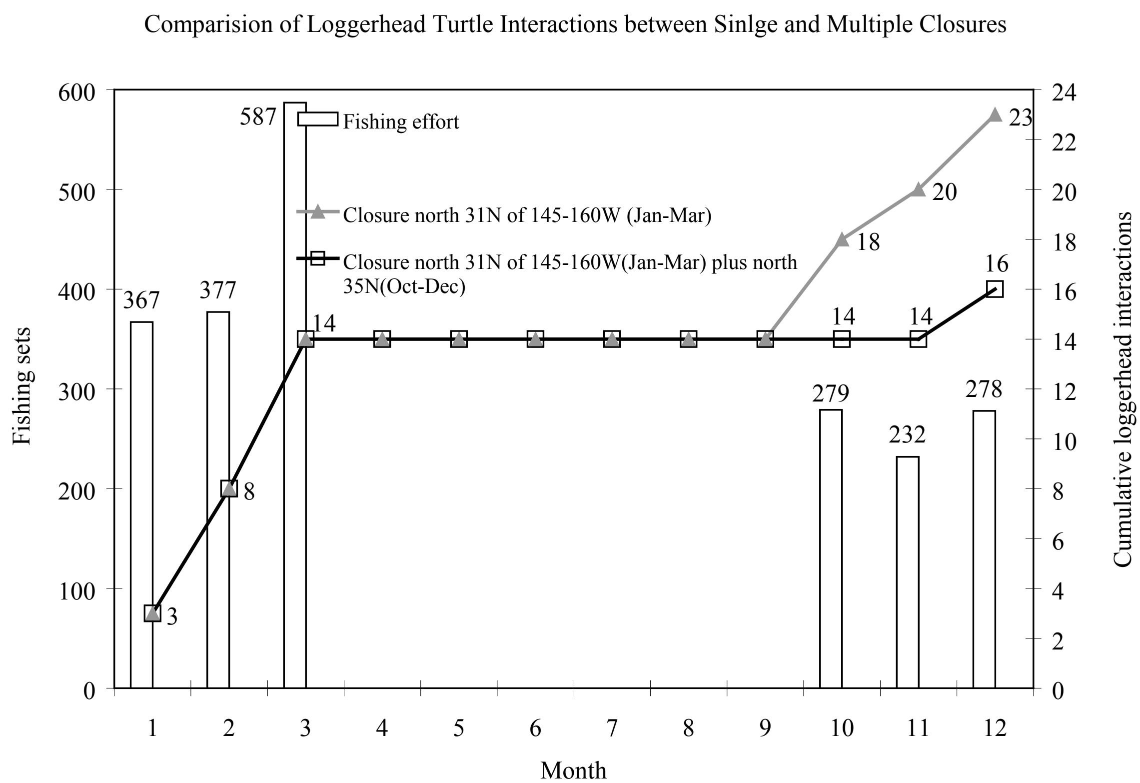


Figure 14. Effect of multiple closures on an October–March fishing season.

when the caps on sea turtle interactions would likely be reached under these different scenarios. The simulations can be extended to examine a wide array of policy options, such as using a multiple-year cap on loggerhead and leatherback turtle interactions or other policy innovations.

The study shows that simulation can be a useful tool for investigating the fishery management decision-making process. Another modeling approach might be to formulate the same research question using programming optimization, but this would involve a large number of decision variables. In reality, this would not be feasible because of the difficulty of implementing fisheries policies with a large number of variables. Also, the optimization approach would need to rely on unrealistic assumptions, such as the fisheries industry is at profit maximization and fishers have perfect knowledge of the area and timing with maximum returns. On the contrary, the Hawaii longline fisheries are highly mobile and usually deal with a great degree of uncertainty. Besides the programming optimization method, there are other alternative approaches. Dr. Rita Curtis (Curtis and Hicks, 2000) applied random utility *models* to create a behavioral model of the fishers' time-area choice. This approach considered that fishers respond to time-area closures and reallocate effort to open areas and alternative, open fisheries (e.g., the tuna longline sector) with the highest expected net revenue. However, this approach lies outside the bounds of this study where the swordfish sector was the sole focus.

By examining the seasonal and spatial distributions of economic returns and sea turtle interactions, simulation analysis provides fishery managers with more insights about the tradeoffs among policy alternatives. Both economic returns from the Hawaii-based longline swordfish fishery and interactions with loggerhead sea turtles are much higher during the first 3 months of the year. However, instead of applying a seasonal closure (e.g., a January closure) to the entire fishing area to reduce the level of interactions, which may cause substantial economic loss, a partial seasonal area closure could be a better policy option, allowing fishing opportunities to continue during the high fishing season. Without any time-and-area closures, the Hawaii-based longline swordfish fishery may lose opportunities for extended swordfish fishing as a result of reaching the loggerhead interaction cap. For example, the difference in net revenue returns between a no time-and-area closure scenario and a partial seasonal closure could be as great as \$3.7 million (in 2005 nominal value) under the 1994 pattern of fishing effort. A scenario analysis also showed that under a partial seasonal area closure, using all of the allocated swordfish fishing certificates in the high fishing season (e.g., by April, as in 1994) would result in higher economic returns than a year-round effort allocation. The difference in net revenue returns is estimated at \$2.0 million, based on reaching 17 loggerhead turtle interactions.

Monthly distribution of fishing effort (number of fishing sets) depends on the fishers' behavior. Under certain fishing effort patterns, a partial seasonal area closure may reduce the loggerhead turtle interactions to below the cap. Under the current cap of 17 loggerhead turtle interactions, one policy option could be to reduce or raise the annual fishing effort limit so as to maximize economic returns across various fishing effort patterns by a partial seasonal area closure, such as a closure north of 31° N from 145 to 160° W from January to March. However, the risk of this policy option is that annual loggerhead turtle interactions may always reach the maximum number of 17, which in turn could cause a sudden closure, as happened in 2006.

In the case that fishing effort mostly occurs in the first and fourth quarters, additional closures from north of 35° N latitude in October–December could be applied to maintain the fishing season in the fourth quarter, especially when more than 35% of swordfish fishing certificates (more than 800 certificates) are still available after September. This multiple time-and-area- closure scenario shows that the expected number of loggerhead turtle interactions would be reduced from 23 to 16 based on an October to March fishing season pattern (Figure 14), which makes it possible for the fishery participants to receive additional economic returns by continuing to fish under the current cap of loggerhead turtle interactions.

The GAMs used to predict sea turtle interactions in this paper are based on observer data from 1994 to 2006. Thus, the data provide only limited information on spatial and temporal interaction rates with sea turtles under the 2004 regulatory measures on swordfish fishing gear and bait. Although the 2004 regulations do not appear to have changed the seasonal and spatial pattern of loggerhead turtle interactions, a longer time series of observer data on longline swordfish fishing under the new gear restrictions and their loggerhead turtle interactions are needed to improve accuracy of the model predictions. For example, the prediction for loggerhead turtle interactions in 2007 was not as predicted the previous 2 years.

Sea turtle interactions are affected by fishing gear, fishing practices, and also by sea surface temperature. Oceanographic changes from El Niño or La Niña may cause variations in sea surface temperature, making the distribution of sea turtle and swordfish habitats dynamic over time and space. Strong La Niña conditions during December 1998, for example, made the eastern Pacific cooler than usual, and the cool water extended farther westward than usual. Strong El Niño conditions in December 1997, in contrast, extended warm water all along the equator from the western Pacific to the eastern Pacific.[14] The longline observer program and the Turtle Watch Program are important in collecting reliable interactions data and helping to communicate information about changes in turtle habitat to fishers.

[14] http://www.pmel.noaa.gov/tao/elnino/la-nina-story.html

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APPENDIX I

Comparison between K-P loggerhead turtle GAM and Updated Model

Variables	K-P GAM	Updated GAM
1) Year	Categorical	Categorical
2) Month	Categorical	Continuous by incorporating daily variations
3) Fishing method	Three trip types: tuna, swordfish, and mixed trip	Two set types: shallow set and deep set – defined by the number of hooks per float
4) Location	Latitude and longitude	Latitude and longitude
5) Oceanographic condition	Sea surface temperature	Sea surface temperature
6) Moon	Moon phase	Moon phase
Method	Stepwise procedure	Stepwise procedure
Final model	~ year + month + s(latitude) + s(longitude) + s(sea surface temperature) + s(moon phase)	~ year + s(month) + s(latitude) + s(longitude) + s(sea surface temperature) + s(hooks per float) + moon phase
Data set	2812 observer sets (1994-1998); 100 bootstrap times for 95% variability bands	27,483 observer sets (deep sets = 22,368, shallow sets = 5115) (1994-2006); 1000 bootstrap times for 95% confidence interval

APPENDIX II

Loggerhead Turtle Interactions, Swordfish Catch, and Economic Return per 1000 Hooks of the Hawaii-Based Longline Swordfish Fishery by Month

Month	Loggerhead Interactions per 1000 hooks[1]		Swordfish Catch per 1000 hooks[2]	Net Revenue Return per 1000 hooks[2]
	1994-2001	2004-2006 Mar.	1994-2006 Mar.	1994-2006 Mar.
1	0.2355	0.0328	10.32	$4,671
2	0.1542	0.0233	12.64	$5,340
3	0.0952	0.0130	14.25	$3,926
4	0.0525	0.0040	12.25	$2,917
5	0.0170	0.0010	8.72	$1,546
6	0.0125	0.0007	8.98	$2,880
7	0.0202	0.0051	6.79	$2,126
8	0.0581	0.0045	3.37	$958
9	0.0554	0.0084	2.66	$1,505
10	0.0902	0.0183	5.32	$741
11	0.0923	0.0111	8.52	$1,592
12	0.0814	0.0108	9.24	$1,709

[1] The loggerhead turtle interaction rates are based on the loggerhead turtle interaction GAM model.
[2] Swordfish catch rates and net revenue rates are based on fish catch (kept) in the Hawaii-based longline logbook data. Net revenue is in 2005 nominal value.

APPENDIX III

Loggerhead Turtle Interactions, Swordfish Catch, and Economic Return per 1000 Hooks of the Hawaii-Based Longline Swordfish Fishery by Latitude

Latitude	Loggerhead Interactions per 1000 hooks[1]		Swordfish Catch per 1000 hooks[2]	Net Revenue Return per 1000 hooks[2]
	1994-2001	2004-2006 Mar.	1994-2006 Mar.	1994-2006 Mar.
23° N	0.0147	0.0003	4.19	$1,263
24° N	0.0182	0.0007	5.72	$1,708
25° N	0.0219	0.0008	7.09	$2,128
26° N	0.0239	0.0013	7.98	$2,414
27° N	0.0295	0.0026	8.27	$2,262
28° N	0.0632	0.0047	11.22	$3,013
29° N	0.0739	0.0074	12.26	$3,267
30° N	0.1089	0.0097	13.37	$4,401
31° N	0.1554	0.0165	13.66	$4,525
32° N	0.2146	0.0258	15.48	$5,757
33° N	0.2554	0.0291	14.35	$4,585
34° N	0.1908	0.0296	14.55	$3,093
35° N	0.1721	0.0229	14.06	$1,859
36° N	0.1877	0.0144	13.08	$1,638
37° N	0.2262	0.0118	13.34	$1,438
38° N	0.2465	0.0121	12.65	$347
39° N	0.2356	0.0078	12.36	$252
40°N	0.2881	0.0155	10.94	$1,231
41° N	0.3673	0.0261	10.87	$83
42° N	0.3737		9.50	-$417
43° N	0.3499		7.71	-$1,498
44° N	0.2109		7.01	-$1,373
45° N	0.1824		2.02	-$1,055

[1] The loggerhead turtle interaction rates are based on the loggerhead turtle interaction GAM model.

[2] Swordfish catch rates and net revenue rates are based on fish catch (kept) in the Hawaii-based longline logbook data. Net revenue is in 2005 nominal value.

APPENDIX IV

Distribution of Shallow Sets and Loggerhead Turtle Interactions by Latitude

	1994–2006 Mar				2004–2006 Mar			2007 (Jan–Mar)	
	Observer		Logbook		100% Observer			100% Observer	
Latitude	Sets	Logger-head	Sets	Predicted Logger-head	Sets	Observed Logger-head	Predicted Logger-head	Sets	Observed Logger-head
≥ 41° N	12	0	264	60	3	0	0.068	0	0
40–41° N	17	0	96	19	4	0	0.074	0	0
39–40° N	15	0	151	30	10	0	0.094	0	0
38–39° N	118	4	376	60	81	1	0.659	0	0
37–38° N	168	13	385	45	124	2	1.181	0	0
36–37° N	144	17	487	72	52	0	0.546	0	0
35–36° N	114	2	605	77	37	1	0.481	1	0
34–35° N	126	11	782	111	42	0	0.863	76	0
33–34° N	178	22	1,002	178	58	1	1.380	164	1
32–33° N	397	30	1,371	195	283	6	6.328	172	2
31–32° N	820	33	2,522	259	656	16	10.531	270	6
30–31° N	464	24	3,364	291	235	1	2.548	180	2
29–30° N	501	29	4,080	246	213	0	1.450	32	0
28–29° N	385	10	3,196	167	143	0	0.695	54	0
27–28° N	235	1	2,211	57	112	0	0.333	14	1
26–27° N	265	1	2,867	51	178	0	0.317	2	0
25–26° N	417	2	2,987	51	247	0	0.194	0	0
24–25° N	289	5	2,862	43	110	0	0.071	0	0
23–24° N	130	1	2,053	26	13	0	0.004	0	0
22–23° N	44	0	365	3	23	0	0.008	0	0
21–22° N	13	0	171	1	0	0	0.000	0	0
20–21° N	27	0	422	1	0	0	0.000	0	0
19–20° N	149	0	2,238	4	1	0	0.000	0	0
18–19° N	37	0	749	1	1	0	0.000	0	0
17–18° N	14	0	36	0	0	0	0.000	0	0
< 17° N	36	0	99	0	0	0	0.000	0	0
Total	5,115	205	35,741	2,048	2,626	28	27.825	965	12

[1] Integer of predicted interactions from the GAM.
Data sources: 1) NMFS PIRO Observer Program; 2) Hawaii-based Longline Logbook Data

APPENDIX V

Distribution of Shallow Sets and Loggerhead Turtle Interactions by Longitude

Longitude	1994–2006 Mar				2004–2006 Mar			2007 (Jan–Mar)	
	Observer		Logbook		100% Observer			100% Observer	
	Sets	Logger-head	Sets	Predicted Logger-head[1]	Sets	Observed Logger-head	Predicted Logger-head	Sets	Observed Logger-head
> 175° W	4	0	1,943	95	18	0	0.053	0	0
174–175° W	22	0	562	33	9	0	0.036	0	0
173–174° W	92	2	742	42	14	0	0.053	2	0
172–173°N	99	3	806	38	27	0	0.120	7	0
171–172° W	59	1	701	44	23	0	0.101	6	1
170–171° W	83	1	701	42	28	0	0.132	10	0
169–170° W	98	3	670	48	40	0	0.120	9	0
168–169° W	126	3	814	52	75	1	0.416	7	0
167–168° W	125	0	733	44	106	0	0.694	36	0
166–167° W	175	6	675	45	117	0	0.816	17	0
165–166° W	133	8	670	46	88	0	0.241	5	0
164–165° W	157	3	826	62	127	2	0.522	18	0
163–164° W	109	4	1,022	84	64	0	0.365	52	1
162–163° W	176	26	1,208	94	78	0	0.170	35	0
161–162° W	205	8	1,609	88	91	1	0.462	31	1
160–161° W	242	4	2,151	101	119	0	0.521	43	1
159–160° W	267	3	2,563	69	125	1	1.323	51	0
158–159° W	365	3	3,427	67	157	2	1.827	31	0
157–158° W	358	3	2,071	57	243	1	3.168	48	2
156–157° W	413	15	1,873	47	293	9	5.096	57	3
155–156° W	235	7	1,517	45	158	6	2.933	49	0
154–155° W	192	13	1,055	47	97	0	1.234	45	1
153–154° W	153	4	932	52	74	0	1.177	53	1
152–153° W	95	4	775	53	34	0	0.558	98	1
151–152° W	104	5	776	49	44	0	0.907	45	0
150–151° W	103	15	710	63	48	0	1.010	63	0
149–150° W	110	6	588	71	57	1	1.003	25	0
148–149° W	85	8	567	56	46	1	0.554	39	0
147–148° W	56	7	580	59	12	0	0.184	33	0
146–147° W	90	9	420	60	40	1	0.480	15	0
145–146° W	105	3	467	60	49	1	0.639	5	0
144–145° W	71	3	407	58	38	1	0.308	27	0
143–144° W	54	6	332	79	18	0	0.116	3	0
142–143° W	42	5	215	38	9	0	0.0929	0	0
141–142° W	42	2	184	18	22	0	0.144	0	0
140–141° W	26	0	85	9	19	0	0.132	0	0

139–140° W	17	1	53	6	8	0	0.0596	0	0
138–139° W	41	2	45	6	11	0	0.0595	0	0
≤ 138° W	101	5	266	21	0	0	0	0	0
Total	5,115	205	35,741	2,048	2,626	28	27.828	965	12

[1]Integer of predicted interactions from the GAM.
Data sources: 1) NMFS PIRO Observer Program; 2) Hawaii-based Longline Logbook Data

APPENDIX VI

Loggerhead Turtle Interactions, Swordfish Catch and Economic Return per 1000 Hooks of the Hawaii-Based Longline Swordfish Fishery by Longitude

	Loggerhead Interactions per 1000 hooks[1]	Swordfish Catch per 1000 hooks[2]	Net Revenue Return per 1000 hooks[2]	
Longitude	**1994-2001**	**2004-2006 Mar**	**1994-2006 Mar**	**1994-2006 Mar**
183° W	0.1169		11.13	$1,812
182° W	0.2139		11.82	$1,370
181° W	0.0675		7.50	$992
180° W	0.0511		8.68	$1,988
179° W	0.0536		9.80	$2,288
178° W	0.0503		11.50	$2,427
177° W	0.0334	0.0020	11.79	$2,620
176° W	0.0442	0.0048	13.47	$3,028
175° W	0.0740	0.0028	10.99	$2,161
174° W	0.0705	0.0047	12.82	$3,691
173° W	0.0651	0.0051	12.37	$3,227
172° W	0.0641	0.0055	12.64	$3,118
171° W	0.0816	0.0060	14.61	$3,668
170° W	0.0831	0.0045	14.38	$3,865
169° W	0.1032	0.0052	13.94	$3,874
168° W	0.0763	0.0060	12.97	$3,444
167° W	0.0965	0.0073	14.95	$4,703
166° W	0.0982	0.0077	13.52	$4,078
165° W	0.1006	0.0035	11.65	$3,075
164° W	0.1120	0.0067	10.62	$2,491
163° W	0.1156	0.0072	10.75	$3,017
162° W	0.0906	0.0039	8.22	$2,222
161° W	0.0689	0.0054	6.32	$1,794
160° W	0.0514	0.0083	5.48	$1,744
159° W	0.0276	0.0155	4.53	$1,467
158° W	0.0275	0.0141	4.63	$2,657
157° W	0.0353	0.0195	7.34	$2,055
156° W	0.0334	0.0235	7.66	$2,357
155° W	0.0402	0.0147	8.07	$2,429
154° W	0.0627	0.0194	10.08	$3,172
153° W	0.0812	0.0182	12.99	$3,892
152° W	0.0828	0.0150	11.49	$3,141
151° W	0.0847	0.0252	11.53	$3,139
150° W	0.1389	0.0258	11.82	$3,548
149° W	0.1566	0.0195	12.03	$3,456
148° W	0.1214	0.0166	12.50	$3,329

147° W	0.1381	0.0149	13.29	$3,218
146° W	0.2066	0.0190	12.93	$3,641
145° W	0.1830	0.0110	14.50	$4,859
144° W	0.2153	0.0089	14.02	$3,871
143° W	0.3190	0.0061	15.82	$4,830
142° W	0.2335	0.0099	15.13	$3,955
141° W	0.1383	0.0093	14.56	$3,394
140° W	0.1642	0.0071	9.66	$2,035
139° W	0.2225	0.0068	11.15	$2,886
138° W	0.1195	0.0056	11.86	$2,162
137° W	0.2097		16.42	$3,938
136° W	0.2615		10.64	$3,756
135° W	0.0881		10.33	$2,562
134° W	0.0702		14.34	$3,977
133° W	0.1297		12.37	$2,435
132° W	0.0487		11.65	$1,284

[1]The loggerhead turtle interaction rates are based on the loggerhead turtle interaction GAM.
[2]Swordfish catch rates and net revenue rates are based on fish catch (kept) in the Hawaii-based longline logbook data. Net revenue is in 2005 nominal value.