Efficacy and Commercial Viability of Regulations Designed to Reduce Sea Turtle Interactions in the Hawaii-Based Longline Swordfish Fishery

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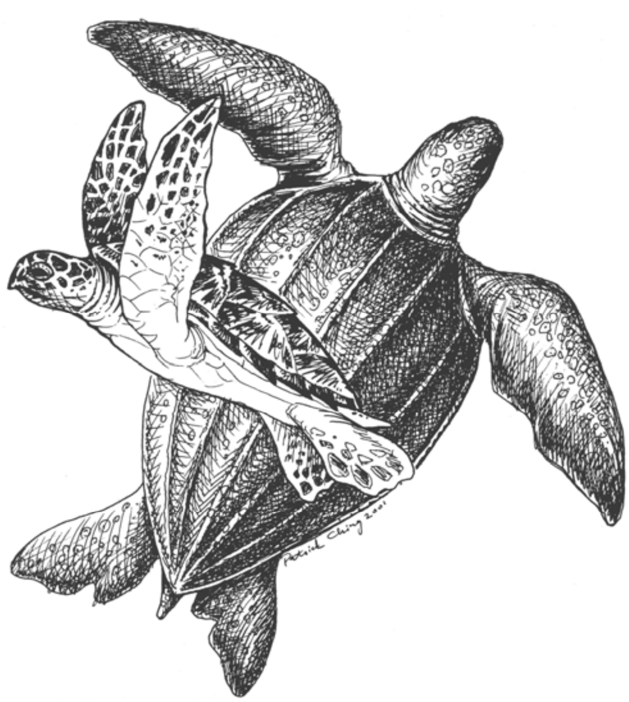
Eric Gilman, Fisheries Bycatch Program Director, Blue Ocean Institute, and University of Tasmania School of Geography and Environmental Studies. E-mail: egilman@blueocean.org

Donald Kobayashi, U.S. NOAA Fisheries, Pacific Islands Fisheries Science Center, and University of Technology, Department of Environmental Sciences. E-mail: Donald.Kobayashi@noaa.gov

Tom Swenarton, U.S. NOAA Fisheries, Pacific Islands Regional Office. E-mail: Tom.Swenarton@noaa.gov

Paul Dalzell & Irene Kinan, Western Pacific Regional Fishery Management Council. E-mail: Paul.Dalzell@noaa.gov, Irene.Kinan@noaa.gov

Nigel Brothers, Marine Ecology and Technology Consultant. E-mail: brothersbone@yahoo.com.au



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Western Pacific Regional Fishery Management Council
1164 Bishop Street, Suite 1400
Honolulu, Hawaii 96813 USA
Email: info.wpcouncil@noaa.gov
http://www.wpcouncil.org/

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SUMMARY

Analyses of Observer Program Data for the Hawaii-Based Longline Swordfish Fishery for:

(i) Effects of Sea Turtle Regulations on Sea Turtle Interactions, Catch Rates of Retained Marketable Species and Catch Rate of Sharks;
(ii) Economic Viability and Potential for Temporal or Spatial Closures to Reduce Turtle Captures;
(iii) Comparison Between 2005 and 2006 Turtle Catch Rates and Temporal Distribution of Effort to Explain the Cause of a Loggerhead Cap Being Reached in 2006 and not 2005; and
(iv) Hook Position of Caught Turtles and Fish

Reducing sea turtle bycatch in pelagic longline fisheries may contribute to the recovery of sea turtle populations. The effectiveness and commercial viability of a turtle avoidance strategy, such as replacing J-shaped hooks with wider circle-shaped hooks, may be fishery-specific, depending on the size and species of turtles and target fish and other differences between fleets. Assessing the effects of turtle avoidance methods in individual fleets is therefore necessary. Regulations based on research conducted in the U.S. North Atlantic longline swordfish fishery came into effect for the Hawaii-based pelagic longline swordfish fishery in May 2004. We conduct the first comprehensive analyses of the U.S. National Marine Fisheries Service observer program database for the Hawaii-based pelagic longline swordfish fishery, in part, to infer possible effects of regulations on turtle interactions, catch rates of retained marketable species and shark capture. There were significant reductions in sea turtle and shark capture rates and reduced proportion of deeply hooked turtles, which may increase post release survival prospects, without comprising target species catches. Results identify effective and commercially viable turtle avoidance methods that may be suitable for use in other pelagic longline fisheries worldwide, potentially resulting in substantial reductions in turtle bycatch in global pelagic longline fisheries.

The existence of confounding factors prevents definitive conclusions regarding single factor effects on turtle and fish interactions. Additional research could be conducted to attempt to identify the relative influence of various known confounding factors on observed differences between the two study periods. Regulations designed to reduce turtle capture rates and proportion of deep-hookings, which came into effect in May 2004, changed the type and size of fishing hook and bait used by the Hawaii-based longline swordfish fleet (from using a 9/0 J hook with squid bait to a wider 10 degree offset 18/0 circle hook with fish bait). Regulations designed to reduce seabird interactions, which came into effect for the Hawaii-based longline swordfish fishery in June 2001, include requirements for swordfish-targeting vessels to night set and dye bait blue, two changes that may affect sea turtle and fish capture rates. Prior to this rule coming into effect, swordfish vessels did not dye bait blue and initiated gear setting an average of 76 minutes earlier than after the requirement for night setting was instituted. Hawaii-based swordfish vessels were subject to the night setting and blue bait requirements for the entire period after the sea turtle regulations came into effect and for the last eight months of the period before the sea turtle regulations came into effect. Another confounding factor is variability in turtle abundance at fishing grounds. Analysis of the location of Hawaii-based longline swordfish effort by quarter for the periods before vs. after the sea turtle regulations came into effect indicate that there was generally no substantial differences in the spatial distribution of effort for these two periods, but there were substantial differences in the temporal distribution of effort.

Turtle Capture Rates
The loggerhead, leatherback and combined turtle species capture rates significantly declined by 90.0%, 82.8% and 89.1%, respectively, from the period before the turtle regulations came into effect to the period after the regulations came into effect. There were also significantly lower turtle catch rates for combined turtle species and individual species for each quarter of each year in the period after the sea turtle regulations came into effect compared to the same quarter of each year before the regulations came into effect, except for leatherback turtle catch rates during the 1st quarter for which the difference was not significant. Thus, differences in temporal distribution of fishing effort between the two periods is not likely a large factor in explaining the differences in turtle CPUE between the two time periods. While it is not possible to determine single factor effects on observed changes in turtle catch rates by the methods used here, these observed reductions in turtle catch rates are consistent with results from controlled experiments on the effects of switching from a J or Japan tuna hook to a wider circle hook and switching from using squid to fish for bait. Changes in the timing of setting and gear retrieval between the two time periods may be another cause of the observed changes in turtle catch rates.

Proportion of Caught Turtles Lightly Hooked vs. Deeply Hooked vs. Entangled
A larger proportion of turtles were lightly hooked (hooked in the mouth or body) or entangled after the sea turtle regulations came into effect vs. for the period before the sea turtle regulations came into effect, which may increase post-release survival prospects. For the period before sea turtle regulations came into effect, 60% of caught hardshelled turtles were deeply hooked (the turtles ingested the hook), 38% were lightly hooked, and 2% were entangled (N = 180, 163 loggerhead turtles). After the regulations came into effect, 63% of caught hardshelled turtles were lightly hooked, 22% ingested the hook, and 15% were entangled (N = 27, all loggerheads). Before the turtle regulations came into effect, 84% of leatherbacks were light hooked, 10% ingested the hook, and 6% were entangled (N = 31). After the turtle regulations came into effect, 100% were light hooked (N = 10). There was no significant difference in the proportion of lightly hooked, deeply hooked, and entangled turtles for the four individual species observed captured between the two time periods before and after the sea turtle regulations came into effect. While it is not possible to determine single factor effects on observed changes in turtle interactions, this observed reduction in proportion of turtle deep hooking is consistent with results from controlled experiments on the effects of switching from a J or Japan tuna hook to a circle hook.[1]

Proportion of Hooked Turtles with vs. without Terminal Tackle Attached Upon Release
For the period before the sea turtle regulations came into effect 40% of hooked turtles (combined species) were released after removing all terminal tackle (hook, line, and in rare cases were it is used, wire trace) (N = 178). After the sea turtle regulations came into effect 67% of hooked turtles were released after removing all terminal tackle (N = 33), which was significantly more than the period before the regulations came into effect. This observed difference between the two time periods is likely a result of the sea turtle regulations requiring Hawaii longline vessels to carry and use turtle release equipment (dip net, dehookers, etc.) while no such requirement was in place prior to the regulations. Also, a smaller proportion of hooked turtles being deeply hooked in the second period, likely a result of switching from a J to circle hook, might have made it easier to remove hooks than when a higher proportion of turtles were deeply hooked.

[1] See Gilman et al. (2006a) for a description of these three different types of longline fishing hooks.

2005 vs. 2006 Turtle Capture Rates and Annual Turtle Interaction Caps
The Hawaii-based longline swordfish fishery reached a cap of 17 loggerhead captures in March 2006 but did not reach this cap for the entire year in 2005. (A total of 12 loggerhead turtles were observed caught in 2005, 9 in the first quarter). There was no significant difference in loggerhead CPUE between the first quarters of 2005 and 2006. Effort in the first quarter of 2006 was 48% higher than in 2005. The higher number of loggerhead captures during the first quarter of 2006 relative to 2005 is a result of the higher fishing effort in 2006, and not the result of a significant difference in loggerhead capture rates.

Proportion of Caught Turtles Alive vs. Dead
For the entire period that the Hawaii longline swordfish fishery has been observed, less than 1% of caught turtles were dead when hauled to the vessel (2 of 255 caught turtles, both from the period before the turtle regulations came into effect), and there was no significant difference in the proportion of alive vs. dead turtles for the four species observed captured between the time periods before and after the sea turtle regulations came into effect. This observed low rate of caught turtles being drowned when hauled to the vessel during gear retrieval is expected for shallow-set longline fisheries with relatively light gear vs. deeper setting longline tuna fisheries with heavier weighted gear.

Rarity of Turtle Captures and Opportunities for Avoiding Turtle Bycatch Hotspots
Turtle captures are relatively rare events: No turtles were caught in 95% of the observed 4,261 sets made by Hawaii-based longline swordfish vessels. Of the 264 turtles caught during the observed period, 77% (202) were caught alone (one turtle caught in a single set) with the remaining 23% (62) being caught in groups of two or more in a single set. Furthermore, of the 231 sets where one or more turtle was caught, 24% (55) were in consecutive sets (two or more sets in a row where one or more turtle was caught per set), and 76% (176) were isolated events (no turtles were caught in sets immediately preceding or following the set where a turtle was observed caught). This indicates that moving vessel position before making another set after a turtle is caught, and employing other methods to avoid real time turtle bycatch hotspots, such as fleet communication programs, could contribute to substantial reductions in turtle catch rates in the Hawaii-based longline swordfish fishery.

Comparison of Individual Vessel's Swordfish and Turtle Catch Rates
Since observer coverage of the Hawaii-based swordfish fishery began, there were a total of 68 Hawaii-based longline vessels that made swordfish sets, of which 53 caught one or more turtles. A comparison of individual vessel's swordfish and sea turtle CPUE reveals that there are several vessels with turtle catch rates substantially above the mean for the fleet but with generally average swordfish catch rates. There are also several vessels with relatively high swordfish catch rates and low turtle catch rates. There was no significant correlation between swordfish and turtle CPUE ($P = 0.27$, $R^2 = 0.02$, $N = 68$), indicating that having a high swordfish catch rate does not necessarily indicate that a vessel will have a high turtle catch rate, and vice versa. The maximum number of turtles caught by a single vessel was 23. The vessel that caught 23 turtles had a sea turtle catch rate 3.8 times the fleet's average, while its swordfish catch rate is slightly below the mean for the fleet. This one vessel caught 9% of the total turtles caught by the fleet. Another vessel had a swordfish catch rate that is 1.8 times higher than the fleet's average and a turtle catch rate that is half the fleet's average. There are three vessels with swordfish catch rates that are 30% or more higher than the mean for the fleet that also have turtle catch rates below the fleet's mean.

Based on the results from this study component we conclude that it is a research priority to investigate differences between vessels with high turtle CPUE and low swordfish CPUE to those with low turtle CPUE and high swordfish CPUE to attempt to identify new strategies to reduce turtle catch rates without compromising economic viability. Additional research can be conducted to determine if the vessels with the relatively high turtle catch rates have had higher fishing effort during periods when turtle catch rates are highest, and to explore if they employ different fishing methods and gear compared to vessels with relatively low turtle catch rates.

Length of Caught Turtles

Average length of caught loggerhead turtles was greater during the period after the sea turtle regulations came into effect than during the period before the regulations when comparing the straight carapace and curved carapace lengths of loggerheads that were (i) mouth hooked and ingested hooks, (ii) foul-hooked in the body or entangled, or (iii) all caught loggerheads. However, differences in length were not significant. For the period prior to the sea turtle regulations coming into effect, straight carapace length of loggerheads was a mean of 56.4 cm (+/- 0.8 cm standard deviation of the mean, N = 155) and mean curved carapace length was 61.3 cm (+/- 0.8 cm standard deviation of the mean, N = 154). For the period after sea turtle regulations came into effect, mean loggerhead straight carapace length was 60.9 cm (+/- 1.9 cm standard deviation of the mean, N = 26) and mean curved carapace length was 66.1 cm (+/- 1.9 cm standard deviation of the mean, N = 26).

When comparing the length of caught loggerhead turtles for just the first quarters of the periods before vs. after the turtle regulations came into effect, again the average length of caught loggerheads for the same three categories was greater during the period after the regulations came into effect, but the differences were not significant. In the period before the turtle regulations, 58% of loggerhead turtles were caught in the first quarter, while 86% were caught in the first quarter during the period after the regulations came into effect. If there are significantly larger or smaller loggerhead turtles at the Hawaii longline swordfish fishing grounds during January-March relative to other seasons, because a higher proportion of loggerheads were caught in the first quarter during the period after the turtle regulations came into effect, this could result in a significantly different mean length of turtles during the two periods. Results eliminate any possible seasonal effect that might have occurred during this first quarter. Too few loggerheads were caught in the other quarters during the period after regulations came into effect to conduct an accurate comparison of loggerhead lengths.

For loggerheads that were hooked in the mouth or ingested the hook, the larger size of turtles caught after the turtle regulations came into effect is likely a result of only larger turtles being capable of fitting the wider 18/0 circle hook in their mouths relative to the narrower 9/0 hooks used before the regulations came into effect. However, it is unclear why larger turtles were caught by entanglement or foul-hooked in the body for the period after the regulations came into effect.

Retained Fish Capture Rates

In the period after sea turtle regulations came into effect, swordfish CPUE was significantly higher by 16.0% while combined tuna species and combined mahimahi, opah, and wahoo CPUE was significantly lower by 50.0% and 34.1%, respectively. The CPUE of combined retained fish for the two periods was not significantly different, and was 2.6% lower in the second period. When analyzed by quarter, differences in CPUE of retained fish were generally consistent with results for the full period, except for swordfish. Results on changes in retained fish CPUE need to be considered with caution because the fishing effort was distributed very differently by quarter for the two periods before and after the turtle regulations came into effect. For example, if there had been more fishing effort during the fourth quarter and less during the first quarter for the period after the regulations came into effect, because swordfish CPUE was significantly higher by 23% during the first quarter but significantly lower by 27% during the fourth quarter, the change in swordfish CPUE for the full period could have resulted in an overall reduction after the regulations came into effect. Observed differences in swordfish and tuna catch rates for the periods when a 9/0 J hook with squid bait was in use vs. the period when a 10 degree offset 18/0 circle hook with fish bait was in use are consistent with results from a controlled experiment in the U.S. North Atlantic longline swordfish fishery.

Shark Capture Rate

Shark combined species CPUE was significantly lower in the period after the regulations came into effect vs. for the period before the turtle regulations came into effect for the full periods and by quarter. This is likely due to the change from squid to mackerel for bait, based on a review of results from studies in the U.S. North Atlantic and Azores pelagic longline fisheries. However, the decrease in shark CPUE could be a result of the change to using blue dyed bait, change in timing of setting and hauling as a result of the requirement for night setting, or other differences between the two time periods before vs. after the sea turtle regulations came into effect.

Spatial and Temporal Closures

We compare the CPUE of swordfish and sea turtles by quarter (January - March, April - June, etc.) for the full study period to determine if seasonal fishery restrictions are feasible to reduce turtle captures. Turtle CPUE was significantly lower in the second quarter than the other three quarters. There was no significant difference in turtle CPUE for the first, third, and fourth quarters, with the highest turtle CPUE point estimate occurring in the third quarter, and second highest in the fourth quarter. Swordfish CPUE was significantly different for each quarter. Swordfish CPUE was significantly lower than all other quarters in the third quarter. The first and fourth quarters had significantly highest and second highest swordfish CPUE, respectively. Based on this, the voluntary historical practice of concentrating 34% of swordfish fishing effort in the second quarter of the year when sea turtle CPUE is lowest has resulted in lower turtle captures than if effort were distributed more evenly by quarter. There is no obvious change to temporal distribution of effort to reduce turtle catch rates that would not have an adverse affect on fishing efficiency: if the fishery were required to reduce effort in the first quarter, which could result in increased effort in the second quarter (when the turtle catch rate is significantly lowest), such as by starting the season later in the year than the current opening on 1 January, this would result in a significant reduction in the swordfish catch rate. Also, because the value of swordfish is highest during the first quarter, restricting fishing effort in this period would result in reduced economic efficiency. Additional research could be conducted to determine how to time the opening of the Hawaii-based longline swordfish fishery to optimize profitability. This assessment should consider factors such as distance to fishing grounds at different seasons, and concomitant temporal differences in fuel costs, as well as the seasonal affect of weather conditions on fishing efficiency. Before instituting a seasonal or spatial closure designed to reduce turtle interactions, analysis of the potential effects on bycatch rates of other sensitive species groups, such as seabirds, sharks, and cetaceans, should also be conducted.

We also compare the (i) distribution of swordfish effort and observed turtle captures and (ii) spatial distribution of turtle CPUE to determine if area closures hold promise to reduce turtle capture rates. There were two areas with relatively high turtle capture rates that had a relatively small proportion of the fleets' fishing effort, indicating that closing areas at a 5 degree cell-scale incorporating these areas would have reduced turtle capture rates without eliminating main fishing areas. The turtle catch rates of these areas are higher than any of the observed turtle catch rates by quarter, and are an order of magnitude higher than the observed turtle capture rate for the full period. The turtle captures in these two areas represent 8.7 % of the total observed 264 caught turtles and 1.4% of the total observed effort made by the Hawaii-based longline swordfish fishery. Closing these observed turtle bycatch hotspots to Hawaii-based longline swordfish vessels at a scale of 5 degree cells might result in displacing effort to other areas where the turtle capture rate might not be significantly different, thus not reducing total turtle captures. There is low certainty that the observed areas of relatively high turtle CPUE will continue to be turtle bycatch hotspots in the future. The locations of high densities of foraging sea turtles will be highly variable, as turtle abundance is correlated with temporally and spatially variable large-scale oceanographic features and short-lived hydrographic features such as eddies and fronts.

Hook Position of Caught Turtles and Retained Fish

We assess the hook position of caught turtles and retained fish to determine if there are significant differences in catch rates on hooks closest to float lines vs. hooks not located immediately next to floats. It is hypothesized that hooks located adjacent to float lines are at shallower depths than the hooks not located immediately adjacent to float lines. Sea turtles spend a majority of their time at depths < 40 m, indicating that setting longline gear deeper than 40 m will reduce turtle captures. Vessels primarily set 4 hooks per basket (between floats): 75% of hooks set to target swordfish by the Hawaii-based longline fleet were in baskets containing 4 hooks. Twenty one percent of hooks set by Hawaii longline vessels to target swordfish were in baskets containing 5 hooks.

There was no significant difference between catch rates of sea turtles combined species, loggerheads, leatherbacks, and hardshelled turtle combined species on hooks in a basket that are not located next to floats vs. hooks located immediately next to floats, and there were nominal differences between sea turtle CPUE point estimates for the two different categories of hooks. This suggests that the depth of baited hooks in these two groups are likely not substantially different, and that all of the hooks are at depths where sea turtles are abundant. Baited hooks may need to be set at depths deeper than the current deepest hook in a basket to result in substantial benefits towards reducing turtle catch rates.

The catch rate of retained fish combined species, retained swordfish and retained tunas are slightly higher on hooks in a basket that are not located next to floats vs. hooks located immediately next to floats. The catch rate of combined retained mahimahi, opah, and wahoo is higher on hooks located closest to floats vs. hooks not located immediately adjacent to floats. Differences in CPUE for swordfish and combined mahimahi, opah, and wahoo were significantly different. Differences in CPUE for all retained fish and combined tuna species were not significantly different. These observations indicate that setting baited hooks deeper may enable the fleet to increase swordfish CPUE potentially without substantially compromising tuna species CPUE.

Priority Research Needs

It is a research priority to assess the differences between Hawaii-based longline swordfish vessels with high vs. low turtle capture rates, including various design and operational differences and differences in temporal and spatial distribution of effort. It is also a priority to assess the efficacy at reducing turtle catch rates and commercial viability of deeper setting of Hawaii-based longline swordfish gear. These studies could result in the identification of new solutions to turtle bycatch in pelagic longline fisheries. Also, it will become increasingly important for onboard observers to record specifics of fishing gear (e.g., hook type) and methods (e.g., method of placing bait on hooks) employed by longline vessels to enable assessments of various factors on turtle capture rates.

1. INTRODUCTION

Many sea turtle populations have dramatically declined in recent decades due to several anthropogenic mortality sources (Spotila *et al*. 1996, 2000; Kamezaki *et al*. 2003; Limpus and Limpus 2003; FAO 2004a,b). Leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) sea turtles could disappear from the Pacific Ocean unless major changes occur soon (Spotila *et al*. 2000; Kamezaki *et al*. 2003; Limpus and Limpus 2003; Dutton et al., In Press; Hitipeuw et al., In Press). Hitipeuw et al. (In Press) report that due to the lack of consistent monitoring, the status of most Pacific leatherback populations is not well understood, but there are indications of a long term decline in leatherback nesting in the western Pacific. Pacific loggerhead nesting populations have been observed to decline 50-90% over the past 50 years (Hatase et al., 2002; Kamezaki et al., 2003). Reducing bycatch of sea turtles in pelagic longline fisheries, in concert with activities to reduce other anthropogenic sources of mortality, may contribute to the recovery of marine turtle populations.

Gilman et al. (2006a) review research on strategies to reduce sea turtle bycatch. Because most research has been initiated only recently, many results are not yet peer-reviewed, published or readily accessible. Moreover, most experiments have small sample sizes and have been conducted over only a few seasons in a small number of fisheries; and many study designs preclude drawing conclusions about the independent effect of single factors on turtle bycatch and target catch rates. In the US North Atlantic longline swordfish fishery, use of 18/0 circle hooks with fish bait significantly reduced sea turtle bycatch rates and the proportion of hard-shell turtles that swallowed hooks vs. being hooked in the mouth compared to narrower 9/0 J hooks with squid bait without compromising commercial viability for some target species (Watson et al., 2005). In the Azores longline swordfish and blue shark fishery, non-offset 16/0 and 18/0 circle hooks caught significantly fewer loggerhead turtles than when fishing with a Japan tuna 3.6 hook, and the proportion of deeply hooked loggerheads was significantly lower when fishing with circle hooks than with a non-offset 9/0 J hook, but it is not possible to determine the effect of the circle hooks on target species CPUE (Bolten and Bjorndal, 2005). In the Ecuador longline tuna fishery, use of a 10 degree offset 18/0 circle hook significantly reduced turtle CPUE relative to fishing with J and Japan tuna hooks, but with a 9.5% reduction in tuna CPUE (Largacha et al., 2005). The effectiveness and commercial viability of a turtle avoidance strategy, including using wider circle hooks and fish instead of squid for bait, may be fishery-specific, depending on the size and species of turtles and target fish and other differences between fleets. Assessing the efficacy of turtle avoidance methods in individual fleets, including the Hawaii fleet, is therefore necessary (Gilman et al., 2006a).

The Hawaii-based longline swordfish fishery was closed for over four years and is now subject to strict management measures, including prescribed use of 10 degree offset 18/0 circle hooks and fish bait (vessels had previously used narrower 9/0 J hooks with squid bait), restricted annual effort, annual limits on loggerhead and leatherback turtle captures, and 100% onboard observer coverage, due to turtle interactions (U.S. National Marine Fisheries Service 2004a). Research conducted in the Hawaii longline fleet on methods to reduce sea turtle bycatch on 18/0 circle hooks vs. 9/0 J hooks both with squid bait (Boggs, 2003, 2004), 16/0 circle hooks vs. 9/0 J hook both with squid bait (LaGrange, 2001), deep daytime sets vs. shallow night sets (Boggs, 2003, 2004), and on camouflaged gear vs. conventional gear (Boggs, 2003, 2004) have not identified effective or commercially viable strategies, but these experiments were small and the deep-setting experiment was not implemented according to the design (Gilman et al., 2006a). The Hawaii longline swordfish fishery has been subject to the hook and bait requirements, limit on annual effort and turtle interactions, and has had 100% onboard observer coverage since 3 May 2004.

The point on “G”-shaped circle hooks is turned in toward the hook shank and the gap between a 4.9 cm-wide 10 degree offset 18/0 circle hook’s point and shaft is smaller than a 4.0

cm-wide 9/0 J hook (Fig. 1).[2] Research conducted to date comparing sea turtle and target species capture rates of 18/0 circle hooks vs. 9/0 J hooks in the U.S. Northwest Atlantic longline swordfish fishery, Azores longline swordfish and blue shark fishery, and on captive turtles generally show that, in these experiments, the circle hook was effective at reducing hard-shelled turtle captures primarily as a result of the size of the hook relative to the size of the turtle, and the circle hook may have been effective at reducing leatherback captures due primarily to the hook's shape (Bolten and Bjorndal, 2003; Watson et al., 2004, 2005; Gilman et al., 2006a). Loggerhead and other hard-shelled turtles tend to get caught in longline gear by biting a baited hook while soft-shelled leatherback turtles tend to get caught by getting foul-hooked on the body and entangled in line (Bolten and Bjorndal 2002 and 2003; Javitech Limited 2002 and 2003; Watson *et al*. 2003a). Leatherbacks may become entangled before they can bite the bait perhaps due to their relatively poor maneuverability (Davenport 1987), however, it is not understood if leatherbacks become entangled first and then hooked as they struggle to free themselves, or if they get hooked first and then entangled.

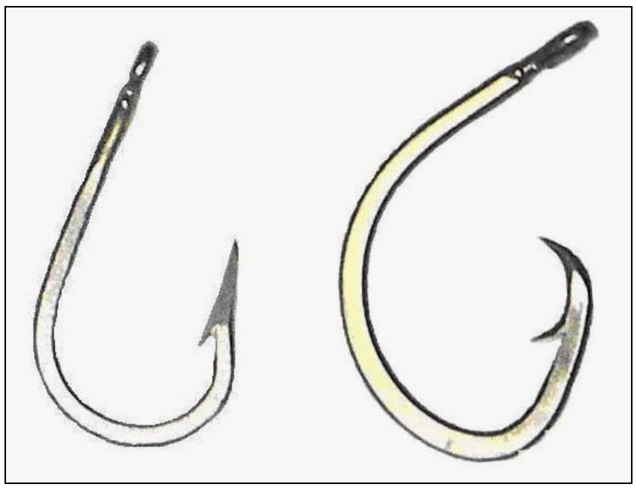


Fig. 1. 9/0 J hook manufactured by Mustad (left) 4.0 cm narrowest width, and 10 degree offset 18/0 circle hook manufactured by Lingren-Pitman 4.9 cm narrowest width (photo E. Gilman). Hooks are oriented so that the narrowest width is horizontal. Differences in hook designs other than narrowest width (i.e. orientation of point, length, gape, bite) and materials may also be important variables affecting sea turtle capture rates and position of hooking.

There is a need for additional research comparing bait types, sizes, and baiting techniques to determine effects on target and turtle CPUE (Gilman et al., 2006a). Watson *et al*. (2004) found no significant difference in turtle capture rate reductions between squid and mackerel bait when used with 18/0 circle hooks. Mackerel bait significantly reduced turtle interactions compared to squid bait when used with J hooks (Watson *et al*. 2004 and 2005). Garrison (2003) found significantly lower leatherback bycatch rates for 7/0, 8/0, and 9/0 J hooks with sardine bait versus 7/0, 8/0, and 9/0 J hooks with squid bait. However, there were confounding factors of differences in the time of day of sets and possibly the depth of gear deployment, which prevent determination of the independent effect of bait type. Watson *et al*. (2004) found that 10 degree offset 18/0 circle hooks with mackerel bait significantly reduced loggerhead and leatherback captures by 88% and 63%, respectively, compared to J hooks with squid bait in the U.S. Atlantic pelagic longline swordfish fleet, but again it is not possible to

[2] There is no standardized, consistent, protocol for measuring the sizes and categorizing the shapes of hooks. The narrowest width of a hook and orientation of the point are likely the most important dimensions to document for research on strategies to reduce sea turtle capture and deep hooking.

determine the single factor effect of bait type. Turtles are believed to feed differently on squid vs. fish. Observations of foraging captive turtles reveal that they tend to progressively eat fish bait in small bites until they completely remove the fish from the hook. When turtles bite a hook containing a fish bait, they carefully remove the remaining fish bait from the hook and avoid ingesting the hook. However, turtles tend to line squid up with their flippers and gulp it down whole, ingesting the hook and bait together, perhaps because they have difficulty biting off pieces of the squid due to squid being rubbery and firm relative to fish (Fig. 2).

Fig. 2. Observations of foraging captive turtles indicate that fish bait tends to be progressively eaten by turtles in small bites, allowing the turtle to detect and avoid consuming the hook, while turtles swallow squid bait whole, consuming the hook with the squid, perhaps because they are unable to bite off pieces of the squid. There is a need for additional research comparing bait types, sizes, and baiting techniques to determine effects on target and turtle CPUE (photos courtesy of Dominy Hataway, U.S. National Marine Fisheries Service Southeast Fisheries Science Center).

We analyze data from the U.S. National Marine Fisheries Service observer program for the Hawaii-based pelagic longline swordfish fishery to provide information to infer the effect of the sea turtle regulations on turtle catch rates, changes in turtle interactions (where turtles are hooked, proportion that are hooked vs. entangled, length of caught turtles, proportion of hooked turtles that are released with hook and line attached vs. after hook removal), catch rate of marketable species, and catch rate of sharks. Additional research could be conducted to attempt to identify the influence of various known confounding factors on observed differences between the two study periods, for instance, by modeling time and area variations of oceanographic features. We compare the spatial distribution of effort with the location of observed turtle captures to determine the promise and economic viability of spatial closures to reduce turtle capture rates. And we compare seasonal differences in swordfish and sea turtle CPUE to determine if a seasonal closure holds promise to reduce turtle capture rates and would be economically viable. We also compare turtle catch rates for 2005 and 2006, the two years after the turtle regulations came into effect when the swordfish fishery was open from 1 January, in an attempt to explain why a cap on loggerhead captures was reached in 2006 but not in 2005. Results may help managers improve the Hawaii regulations and identify new strategies to reduce sea turtle bycatch that may be exportable to other longline fisheries.

We also conduct an analysis of the observer program data on the Hawaii longline swordfish fishery on the hook position of caught turtles and retained fish. Results from this component could identify the potential efficacy at reducing turtle interactions and economic viability of modifying gear design to alter the depth of baited hooks.

2. METHODS

Data from the Hawaii longline observer program are used to observe the following parameters for the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce turtle interactions came into effect:

- Catch rates of sea turtles, retained fish, and sharks;
- Location and timing of fishing effort;
- Proportion of caught turtles alive vs. dead when hauled to the vessel;
- Proportion of caught turtles that were entangled vs. light hooked (hooked in the mouth or in the body) vs. deeper hooking (when hooks are swallowed). If a turtle is observed to be both hooked and entangled, we count it as being hooked only. We reviewed hard copies of observer comment forms to obtain available information on the manner of turtle capture for records that were missing in the electronic database, which occurred primarily for older trips;
- Proportion of caught turtles that are released with hook and other terminal tackle attached vs. are released after all terminal tackle is removed. Information on what portion of terminal tackle remained attached to released turtles is not available from the Hawaii longline observer program electronic database before 22 August 2003. This more detailed information may be available in the hard copy observer files;
- Proportion of sets where turtles were caught that were isolated events vs. were one of two or more sets in a row where one or more turtle was caught, and proportion of caught turtles that were caught alone in a single set vs. sets where two or more turtles were caught;
- Turtle and swordfish catch rates by individual vessels;
- Straight and curved carapace length of caught sea turtles. Because information on lengths of caught turtles is available only for loggerhead turtles for the period after the sea turtle regulations came into effect, we only include loggerheads in this study component. We compare the mean lengths of (a) all caught loggerheads, (b) foul-hooked in the body or entangled loggerheads, and (c) mouth-hooked loggerheads and loggerheads that ingested hooks;
- Catch rates of swordfish and sea turtles to assess the feasibility and commercial viability of instituting seasonal fishery restrictions to reduce turtle interactions; and
- Distribution of swordfish effort and locations of observed turtle captures to determine the feasibility and commercial viability of instituting area closures to reduce turtle captures.

We also analyze data from the Hawaii longline observer program to conduct two additional study components. We determine sea turtle catch rates by Hawaii-based longline swordfish vessels in 2005 and 2006. This study component is included in order to attempt to explain why a cap on loggerhead interactions was met in 2006 but not in 2005. Data from 2004 are not included in this analysis because the swordfish fishery did not open until 23 May in this year, and effort was extremely low (139 sets, 119,263 hooks for the entire year). Finally, we determine the catch rate of sea turtles and retained fish by hook position in a basket (hooks located immediately adjacent to buoy lines vs. hooks in between). This final study component differs from the list of study components above by making observations of the entire period that the Hawaii-based longline swordfish fishery has had onboard observer coverage, and is not broken down into the periods before vs. after the turtle regulations came into effect.

The period covering Hawaii longline swordfish fishing prior to the sea turtle regulations is from 2 March 1994 – 20 February 2002. The period covering the Hawaii longline swordfish fishery after the sea turtle regulations came into effect is from 3 May 2004 – 19 March 2006.

The Hawaii observer program first recorded information from vessels targeting swordfish on 2 March 1994. The regulations designed to reduce sea turtle interactions came into effect on 3 May 2004. There were no swordfish sets between 21 February 2002 and 3 May 2004 due to a temporary closure of this component of the Hawaii longline fleet. The last swordfish set in 2006 was on 19 March. The Hawaii longline swordfish fishery was closed on 20 March 2006 when a cap of 17 loggerhead turtle captures was reached.

All study components analyze data from swordfish-targeting sets only. Prior to the promulgation of regulations to reduce turtle interactions Hawaii longline vessels would conduct mixed trips where they targeted swordfish in some sets and yellowfin and bigeye tuna in other sets of a single trip. The sets where the vessel targeted tuna are not included in this analysis (where gear is usually set deeper than when targeting swordfish).

Several of these analyses are conducted by quarter (e.g., January – March, April – June) in addition to the full period to enable an assessment of possible effects of seasonality and temporal distribution of fishing effort. The location of swordfish sets and turtle captures are presented either in relatively low resolution (5.0 degree cells) or are 'jittered' to introduce noise into positions (random +/- 2.5 degrees from the actual position) to comply with U.S. Government confidentiality requirements.

Probable error of point estimates are reported as nonparametric 95% confidence intervals derived from percentile method bootstrapping at N = 1000. This is a standard resampling technique to address variability when the parametric assumptions cannot be met, when underlying distributions are poorly known because of a small sample size or other considerations such as skewed data and outliers (Efron and Tibshirani, 1986). The chi-square test of heterogeneity is used to determine if there was a significant difference between the period before vs. after the sea turtle regulations came into effect for the (i) proportion of caught turtles that were alive vs. dead when hauled to the vessel; (ii) proportion of caught turtles that were lightly hooked vs. deeply hooked vs. entangled; and (iii) proportion of hooked turtles that were released with vs. without terminal tackle attached.

3. RESULTS

There were 120 observed Hawaii pelagic longline swordfish trips during which 1631 sets of 1,282,748 hooks were made before regulations designed to reduce sea turtle interactions came into effect on 3 May 2004. There were 164 observed trips during which 2631 sets of 2,150,674 hooks were made after the sea turtle regulations came into effect.

3.1. Changes in Turtle Catch Rates

A total of 264 sea turtles were observed captured for the entire study period (0.0767 captures per 1000 hooks based on an aggregation of all data), 223 (0.174 per 1000 hooks based on an aggregation of all data) before the regulations came into effect and 41 (0.019 per 1000 hooks based on an aggregation of all data) after the regulations came into effect. Table 1 provides sea turtle capture rates by the Hawaii longline swordfish fishery before and after the regulations on sea turtle captures came into effect. The combined turtle species, loggerhead, and leatherback capture rates declined by 89.1%, 90.0%, and 82.8% from the period before the turtle regulations came into effect to the period after the regulations came into effect, respectively. Based on non-overlapping nonparametric 95% CIs derived from percentile method bootstrapping at N = 1000, there were significantly lower sea turtle catch rates for combined turtle species and for individual turtle species caught in the period after the sea turtles came into effect compared to the period before the regulations came into effect (Table 1, Fig. 3). There were also significantly lower turtle catch rates for combined turtle species and individual species for each quarter of each year in the period after the sea turtle regulations came into effect compared to the same quarter of each year after the regulations came into effect, except for leatherback turtle catch rates during the 1st quarter where the difference was not significant (Table 1). Due to the rarity of sea turtle captures, some confidence interval estimates of uncertainty for capture rates may be inaccurate, especially in cases of no observed captures, which is why we do not present any confidence interval around these means.

In the first period before the turtle regulations came into effect, 223 turtles were caught in 191 sets (a maximum of 3 turtles were caught in a single set, which occurred 4 times (Fig. 4)). There were 1,439 sets where no turtles were caught in the period before sea turtle regulations came into effect. The 223 turtles were caught by 47 vessels. There were a total of 58 vessels that made swordfish sets during this period. The maximum number of turtles caught by a single vessel was 19, the second highest number of turtles caught by a single vessel was 18 (Fig. 5). The vessel that caught 19 turtles made a total of 46 sets, setting a total of 32,231 hooks during this period, resulting in a sea turtle capture rate of 0.589 captured turtles per 1000 hooks, which is 2.7 times the average turtle CPUE of swordfish-targeting vessels during this period. The vessel that caught 18 turtles made a total of 39 sets, setting a total of 32,914 hooks during this period, resulting in a sea turtle capture rate of 0.547 captured turtles per 1000 hooks, which is 2.5 times the average turtle CPUE.

After the turtle regulations came into effect, 41 turtles were caught in 40 sets (there was only one set where two turtles were caught, all other turtle captures occurred in separate sets (Fig. 6)). There were 2,591 sets where no turtles were caught in the period after turtle regulations came into effect. The 41 turtles were caught by 23 vessels. There were a total of 38 vessels that made swordfish sets during this period. The maximum number of turtles caught by a single vessel was four (two vessels caught four turtles during this period, which were the same two vessels that caught the highest number of turtles in the first period) (Fig. 7). One of the vessels that caught four turtles did so in three sets in one trip, while the other vessel caught four turtles in four separate sets in three trips.

For the full period, of the 231 sets where one or more turtle was caught, 24% (55) were in consecutive sets (two or more sets in a row where one or more turtle was caught), and 76% (176) were isolated events (no turtles were caught in sets immediately preceding or following the set where a turtle was observed caught).

For the full period since the Hawaii-based swordfish fishery has been observed, there were a total of 68 Hawaii-based longline vessels that made swordfish sets, of which 53 caught one or more turtle. Half of the fleet caught < three turtles. The maximum number of turtles caught by a single vessel was 23 (Fig. 8). The vessel that caught 23 turtles set a total of 63,981 hooks during this period, resulting in a sea turtle capture rate that is 3.8 times the average turtle CPUE of swordfish-targeting vessels during this period.

Table 1. Sea turtle capture rates by the Hawaii longline swordfish fishery before and after regulations designed to reduce sea turtle interactions came into effect.

Observed turtle captures, effort, and CPUE	Period									
	2 March 1994 – 20 Feb 2002					3 May 2004 – 19 March 2006				
	1st quarter	2nd quarter	3rd quarter	4th quarter	Full period	1st quarter	2nd quarter	3rd quarter	4th quarter	Full period
Observed Turtle Captures										
Combined species	105	42	22	54	223	30	5	0	6	41
Loggerhead	97	16	18	36	167	24	0	0	4	28
Leatherback	2	15	3	17	37	4	5	0	2	11
Olive ridley	3	6	1	0	10	0	0	0	0	0
Green	2	3	0	0	5	0	0	0	0	0

Unknown	1	2	0	1	4	2	0	0	0	2
Effort										
Number hooks observed	471,212	441,506	126,398	243,632	1,282,748	1,133,875	720,555	46,976	249,268	2,150,674
Number sets observed	602	556	168	305	1,631	1,399	864	56	312	2,631
Turtle CPUE										
Combined species turtle CPUE (number captured per 1000 hooks)	0.223	0.095	0.174	0.222	0.174	0.027	0.007	0.000	0.024	0.019
Combined species CPUE 95% CI	0.179 – 0.272	0.068 – 0.124	0.089 – 0.273	0.164 – 0.281	0.150 – 0.199	0.018 – 0.036	0.001 – 0.014		0.008 – 0.044	0.013 – 0.025
Loggerhead CPUE (number captured per 1000 hooks)	0.206	0.036	0.142	0.148	0.130	0.021	0.000	0.000	0.016	0.013
Loggerhead CPUE 95% CI	0.161 – 0.249	0.020 – 0.056	0.057 – 0.254	0.096 – 0.204	0.109 – 0.152	0.012 – 0.031			0.004 – 0.032	0.008 – 0.019
Leatherback CPUE (number captured per 1000 hooks)	0.004	0.034	0.024	0.070	0.029	0.004	0.007	0.000	0.008	0.005
Leatherback CPUE 95% CI	0.000 – 0.011	0.018 – 0.052	0.000 – 0.055	0.041 – 0.103	0.020 – 0.038	0.001 – 0.008	0.001 – 0.014		0.000 – 0.020	0.002 – 0.008

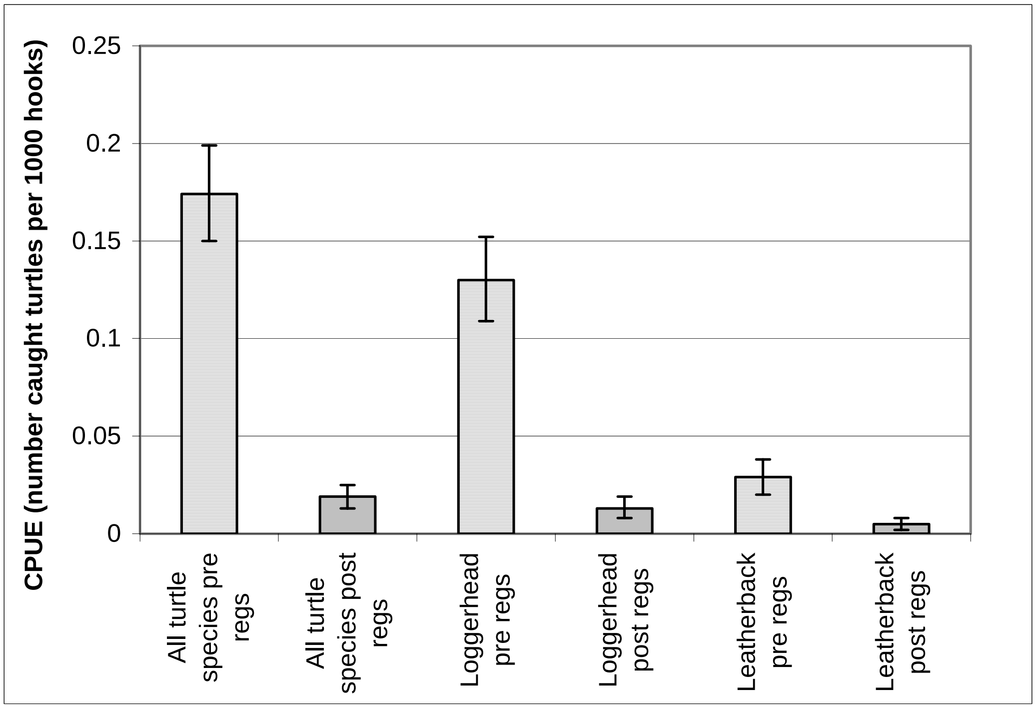


Fig. 3. Sea turtle capture rates (captures per 1000 hooks) in the Hawaii pelagic longline swordfish fishery for combined turtle species, loggerhead turtles, and leatherback turtles, for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

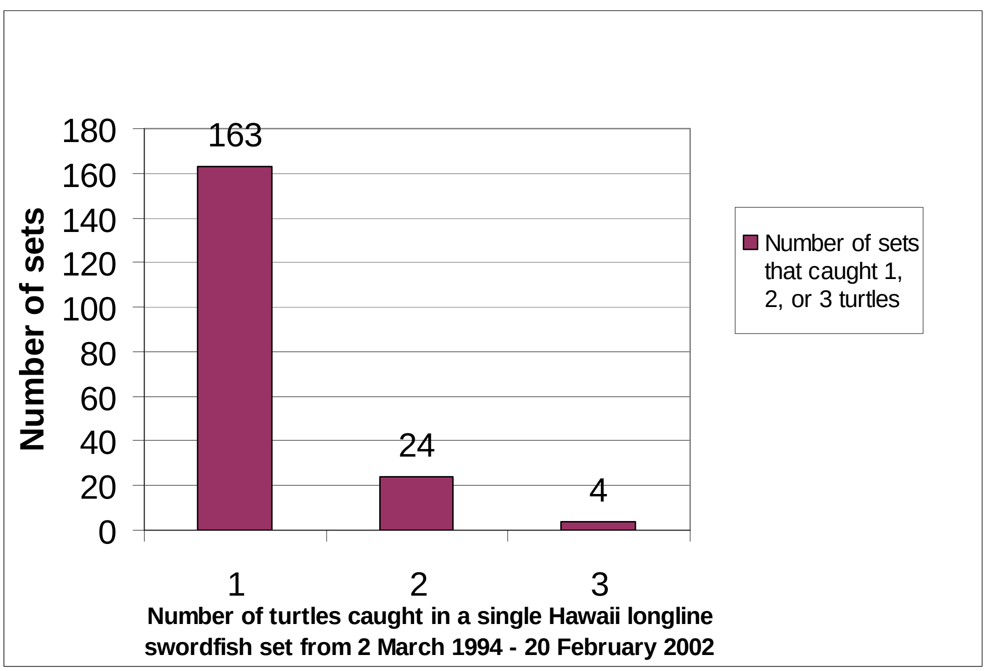


Fig. 4. Number of Hawaii longline swordfish sets that caught 1, 2, or 3 sea turtles during the observed time period before sea turtle regulations came into effect. Zero turtles were caught in 1,439 sets.

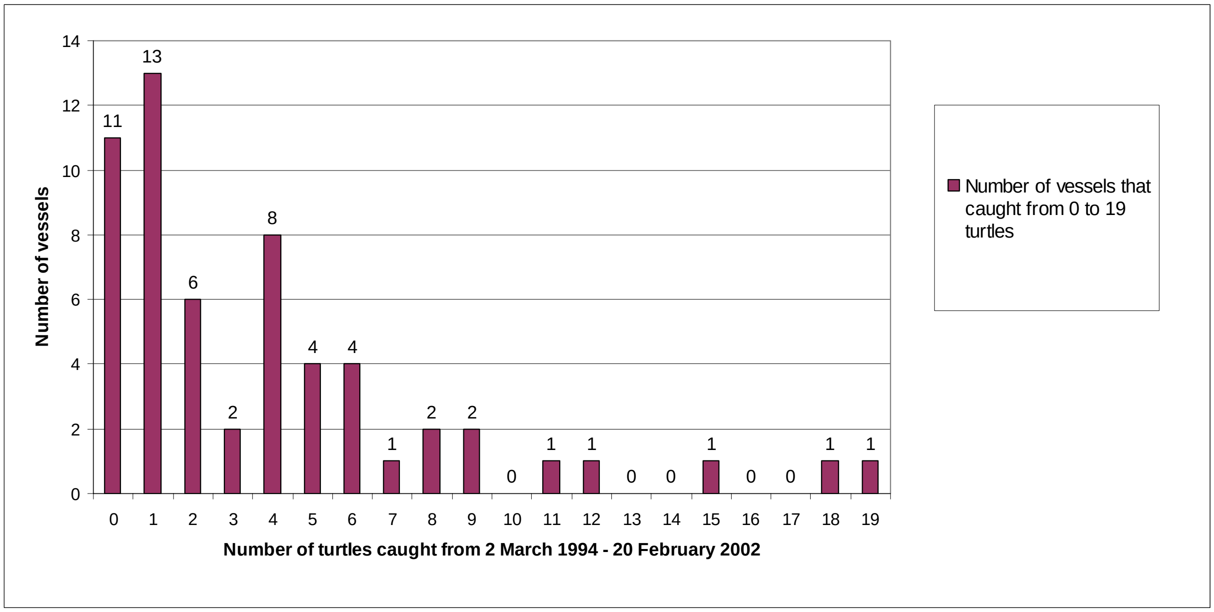


Fig. 5. Number of Hawaii-based longline swordfish vessels that caught from 0 to 19 turtles during the observed period before sea turtle regulations came into effect.

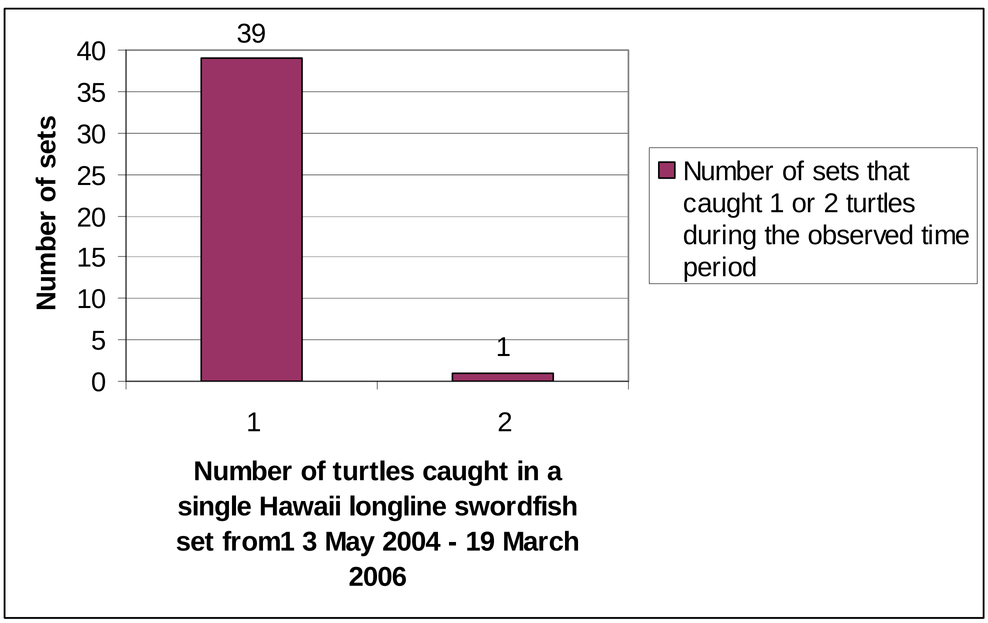


Fig. 6. Number of Hawaii longline swordfish sets that caught 1 or 2 sea turtles during the observed time period after sea turtle regulations came into effect. Zero turtles were caught in 2,591 sets.

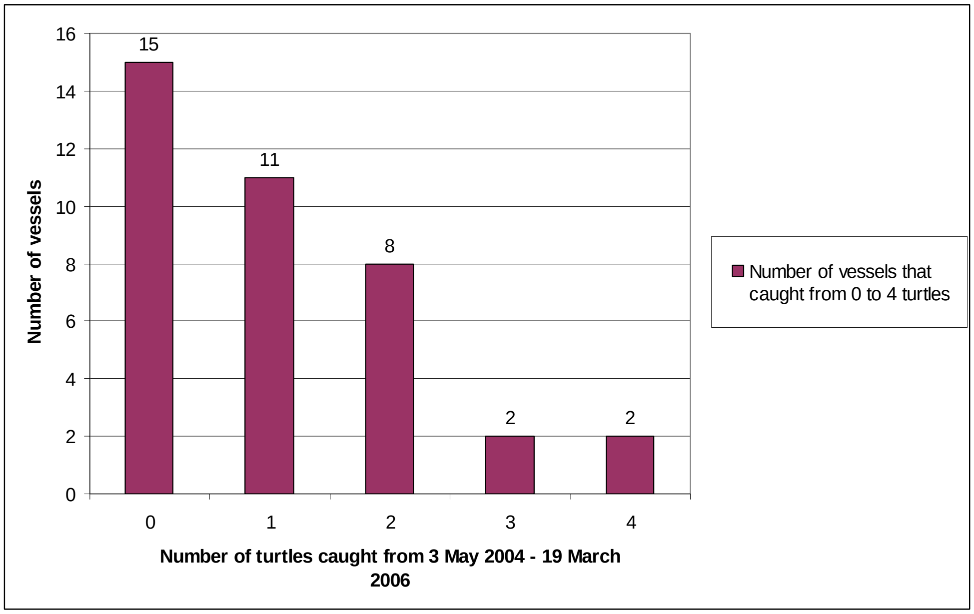


Fig. 7. Number of Hawaii-based longline swordfish vessels that caught from 0 to 4 turtles during the observed period after sea turtle regulations came into effect.

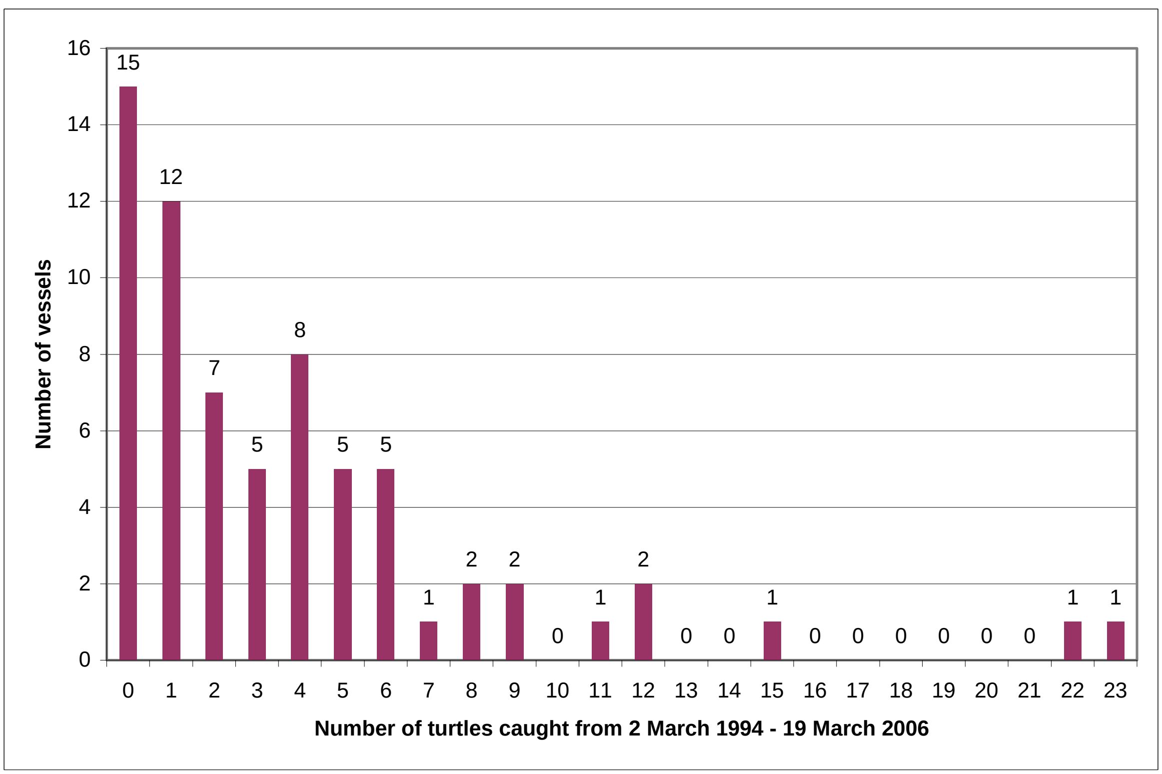


Fig. 8. Number of Hawaii-based longline swordfish vessels that caught from 0 to 23 turtles during the full period that the fishery has had onboard observer coverage.

Figs. 9-12 show the location of Hawaii-based longline swordfish effort by quarter for the period before and after the sea turtle regulations came into effect.

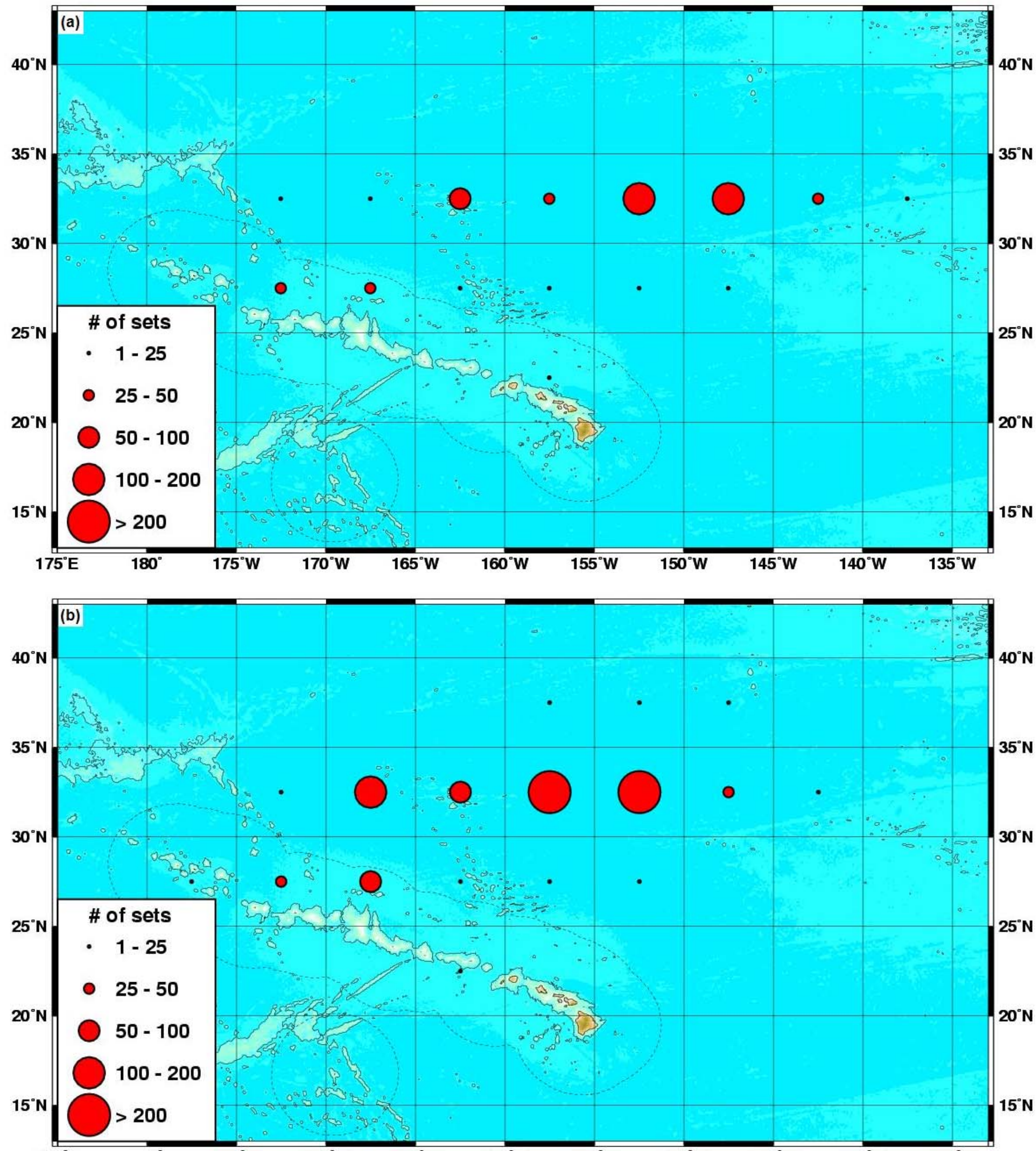


Fig. 9. Location of Hawaii-based longline swordfish sets at 5.0 degree resolution for sets that began in January-March, for (a) 2 March 1994 – 20 February 2002 (N = 602), and (b) 3 May 2004 – 19 March 2006 (N = 1,399).

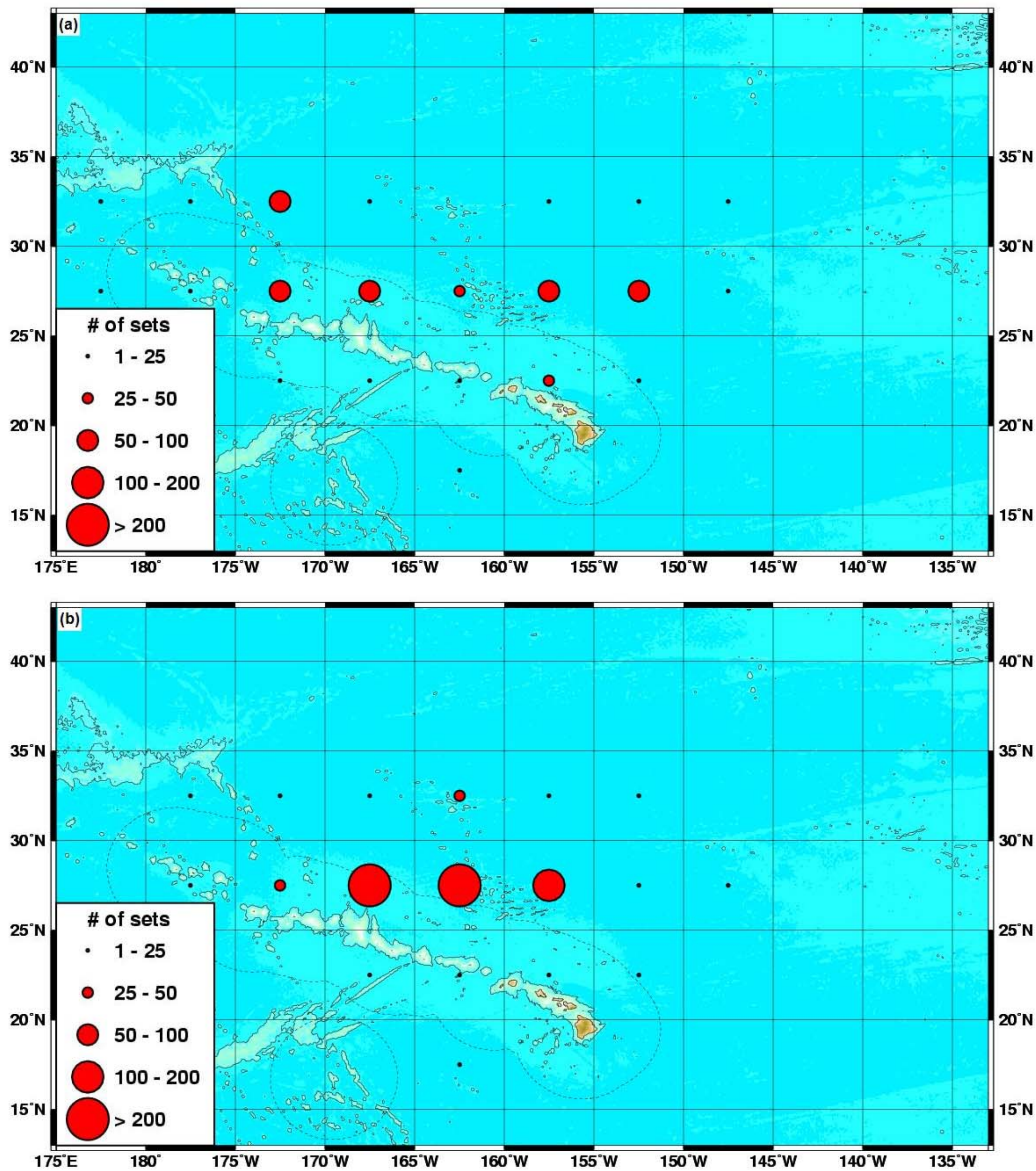


Fig. 10. Location of Hawaii-based longline swordfish sets at 5.0 degree resolution for sets that began in April - June, for (a) 2 March 1994 – 20 February 2002 (N = 556), and (b) 3 May 2004 – 19 March 2006 (N = 864).

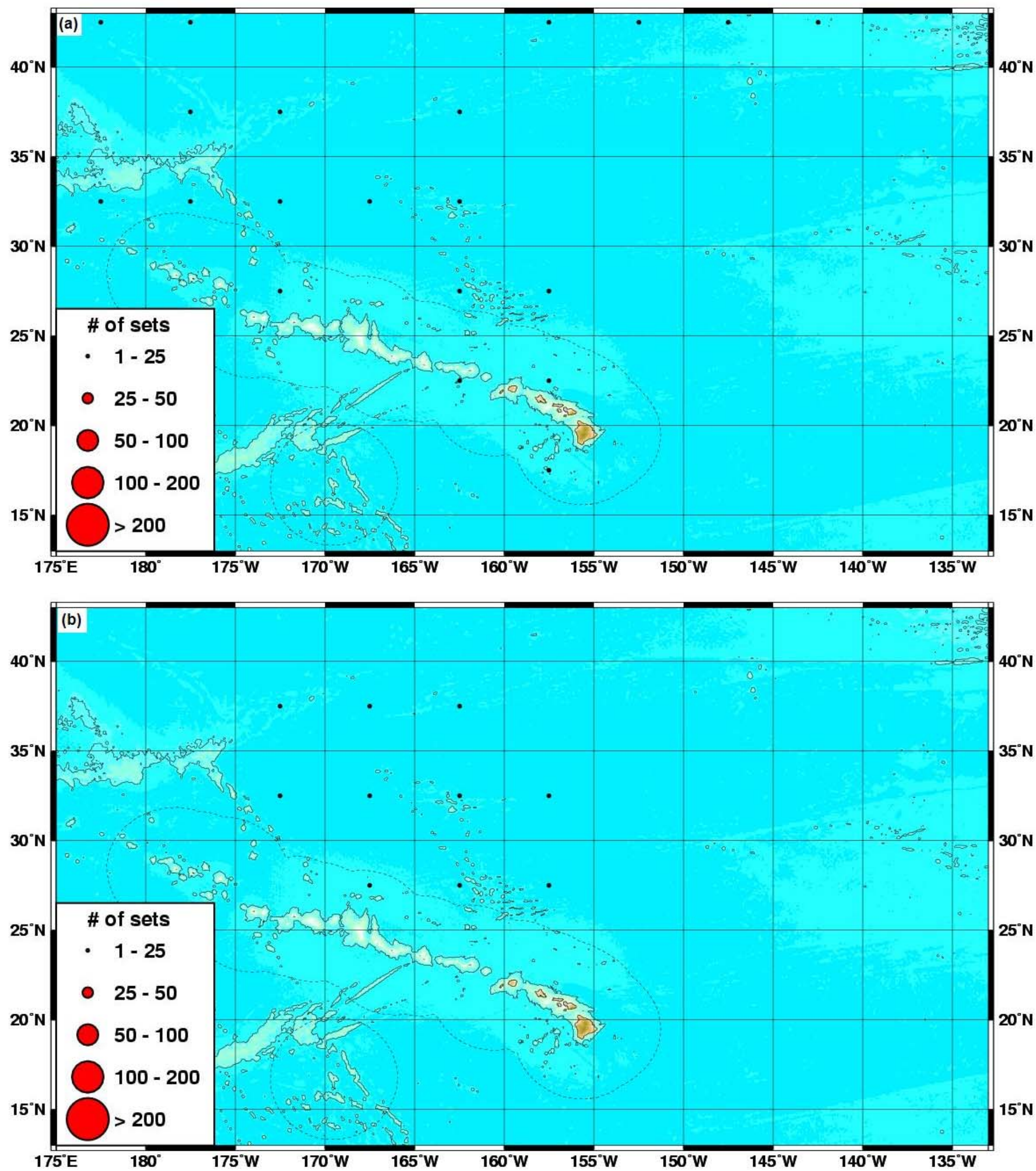


Fig. 11. Location of Hawaii-based longline swordfish sets at 5.0 degree resolution for sets that began in July - September, for (a) 2 March 1994 – 20 February 2002 (N = 168), and (b) 3 May 2004 – 19 March 2006 (N = 56).

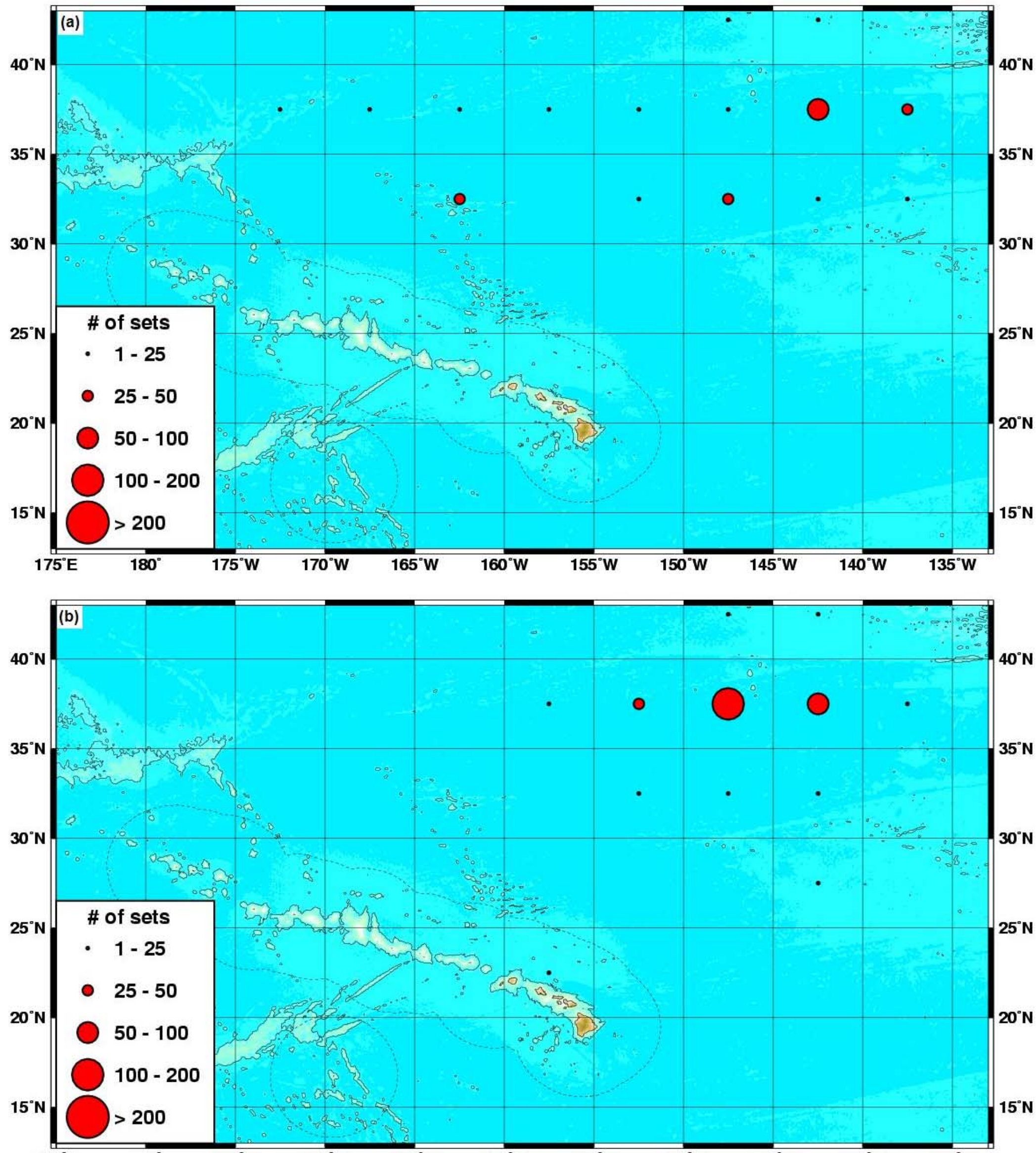


Fig. 12. Location of Hawaii-based longline swordfish sets at 5.0 degree resolution for sets that began in October - December, for (a) 2 March 1994 – 20 February 2002 (N = 305), and (b) 3 May 2004 – 19 March 2006 (N = 312).

3.2. Catch Rates of Retained Fish

Table 2 shows the CPUE of retained fish for the periods before and after the sea turtle regulations came into effect by quarter and for the full periods. For the full periods, based on non-overlapping nonparametric 95% CIs derived from percentile method bootstrapping at N = 1000, swordfish CPUE was significantly higher in the period after the regulations came into effect. Based on overlapping 95% CIs, CPUE of combined tuna species and combined mahimahi, opah, and wahoo were significantly lower in the period after the sea turtle regulations came into effect. Swordfish CPUE increased by 16.0% while combined tuna species CPUE and combined mahimahi, opah, and wahoo CPUE dropped by 50.0% and 34.1%, respectively, from the first to second period. The CPUE of combined retained fish for the two periods was not significantly different, dropping by 2.6% from the first to second period (Table 2, Fig. 13).

When analyzed by quarter, differences in CPUE of retained fish were generally consistent with results for the full period, except for swordfish. Swordfish CPUE was higher for the first two quarters and lower for the second two quarters after the turtle regulations came into effect, and differences were significant for the first, second, and fourth quarters, but not for the third quarter. Swordfish CPUE was 23% and 16% higher during the period after the regulations came into effect for the first and second quarters, respectively. Swordfish CPUE was 9% and 27% lower during the period after the regulations came into effect for the third and fourth quarters, respectively. The CPUE of retained fish combined species was higher in the first two quarters and lower in the second two quarters after sea turtle regulations came into effect, the difference was not significantly different for the first three quarters, but was significantly lower for the fourth quarter. Tuna species CPUE was significantly lower for the period after turtle regulations came into effect for all four quarters. Combined CPUE for mahimahi, opah, and wahoo was lower for the period after turtle regulations came into effect for all four quarter, and the difference was significant for the first and last quarters.

Table 2. Retained fish CPUE (number of fish per 1000 hooks) by the Hawaii-based longline swordfish fishery before and after regulations designed to reduce sea turtle interactions came into effect.

	Retained fish			
CPUE	Swordfish	Tunas [2]	Opah, mahimahi, wahoo	All
Pre regulations (2 March 1994 – 20 Feb 2002)				
1st quarter				
CPUE [1]	14.79	4.86	2.54	22.91
95% CI [1]	14.17 – 15.42	4.47 – 5.27	2.12 – 3.01	21.97 – 23.89
2nd quarter				
CPUE [1]	10.96	3.86	8.08	24.91
95% CI [1]	10.39 – 11.49	3.44 – 4.32	7.00 – 9.14	23.56 – 26.15
3rd quarter				
CPUE [1]	10.69	2.91	4.12	19.65
95% CI [1]	9.36 – 12.20	2.38 – 3.49	2.72 – 6.01	17.52 – 21.87
4th quarter				
CPUE [1]	15.85	7.15	2.23	25.89
95% CI [1]	14.70 – 16.91	5.73 – 8.78	1.74 – 2.79	23.84 – 23.38
Full period				
CPUE [1]	13.29	4.77	4.54	23.87
95% CI [1]	12.89 – 13.73	4.41 – 5.16	4.09 – 5.04	23.11 – 24.64
Post regulations (3 May 2004 – 19 march 2006)				
1st quarter				
CPUE [1]	18.18	3.10	0.88	23.09
95% CI [1]	17.69 – 18.70	2.89 – 3.28	0.76 – 1.00	22.54 – 23.64
2nd quarter				
CPUE [1]	12.76	1.14	7.20	26.29
95% CI [1]	12.31 – 13.18	1.04 – 1.25	6.63 – 7.85	25.52 – 27.12
3rd quarter				
CPUE [1]	9.71	1.26	2.94	17.60
95% CI [1]	8.23 – 11.17	0.88 – 1.65	2.19 – 3.76	15.89 – 19.34
4th quarter				
CPUE [1]	11.64	3.01	0.47	16.33
95% CI [1]	10.90 – 12.34	2.65 – 3.42	0.33 – 0.64	15.48 – 17.25

Full period				
CPUE [1]	15.42	2.39	2.99	23.26
95% CI [1]	15.09 – 15.78	2.27 – 2.51	2.75 – 3.23	22.80 – 23.69

[1] CPUE point estimates and error intervals determined from percentile method bootstrapping at N = 1000.

[2] Albacore, bigeye, skipjack, and yellowfin.

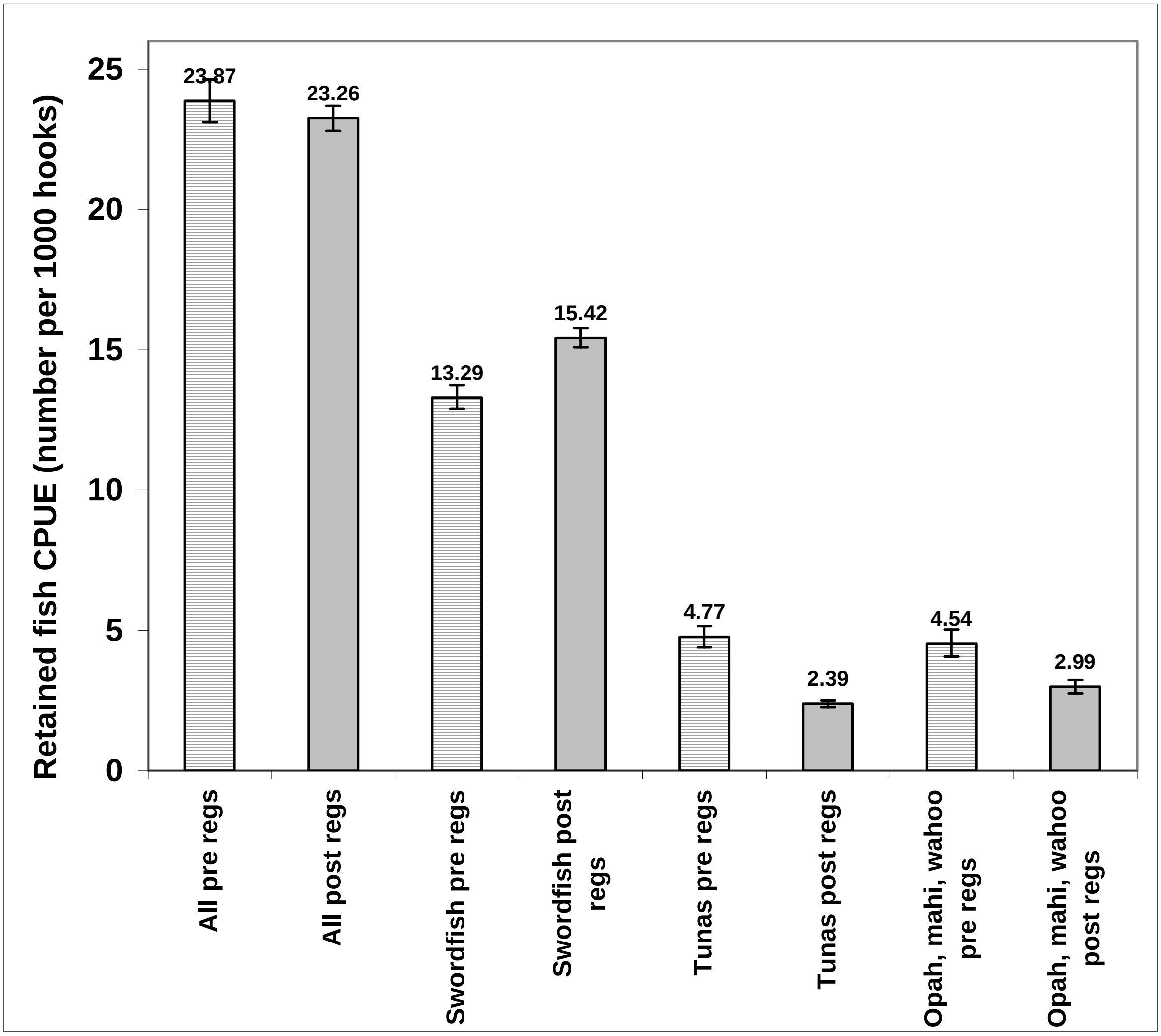


Fig. 13. Retained fish CPUE (number per 1000 hooks) in the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

3.3. Comparison of Individual Vessel Retained Swordfish and Turtle Catch Rates

Fig. 14 is a scatter plot of retained swordfish and turtle (combined species) CPUE by each of the 68 vessels of the Hawaii-based longline swordfish fishery. There was no significant correlation between swordfish and turtle CPUE ($P = 0.27$, $R^2 = 0.02$, $N = 68$). The mean sea turtle CPUE was 0.0935 turtles per 1000 hooks (+/- 0.01 standard deviation of the mean, N = 68, range of 0 – 0.4). The mean swordfish CPUE was 14.74 retained swordfish per 1000 hooks (+/- 0.70 standard deviation of the mean, N = 68, range of 0 – 26.8).

Of these 68 vessels, 53 caught ≥ 1 turtle during the observed period while 15 vessels did not catch a turtle. The two vessels that caught 0 swordfish each made only one fishing trip to target swordfish, both conducted during July (one in 1994 and one in 1996).

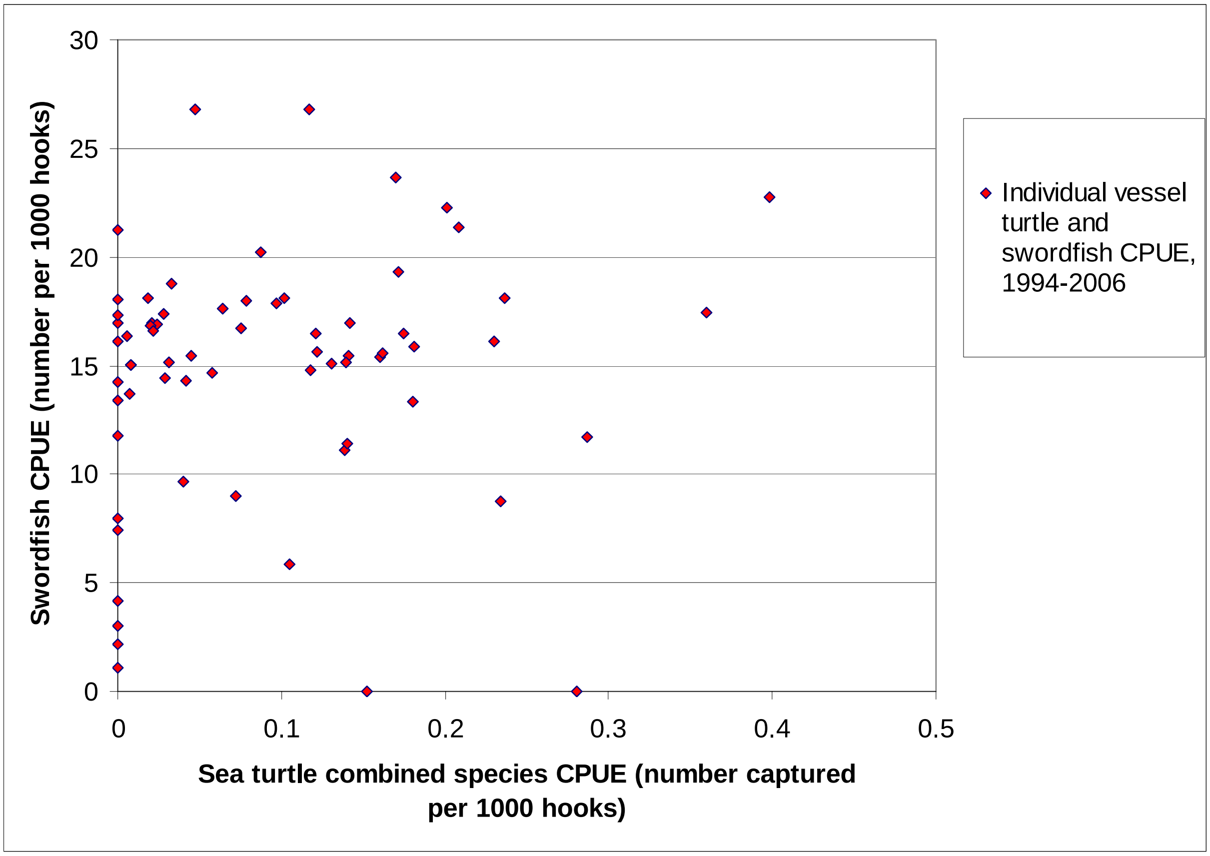


Fig. 14. Catch rate of retained swordfish and sea turtles combined species of individual vessels of the Hawaii-based longline swordfish fishery, 1994-2006 (N = 68).

3.4. Change in Catch Rate of Sharks

Table 3 and Fig. 15 show shark CPUE by quarter and for the full periods for the periods before and after the sea turtle regulations came into effect. Based on non-overlapping nonparametric 95% CIs derived from percentile method bootstrapping at N = 1000, shark CPUE was significantly lower in the period after the regulations came into effect vs. for the period before the turtle regulations came into effect for the full periods and by quarter.

Table 3. Caught sharks combined species CPUE (number per 1000 hooks) by the Hawaii-based longline swordfish fishery before and after regulations designed to reduce sea turtle interactions came into effect.

CPUE	Caught Sharks [2]
Pre regulations (2 March 1994 – 20 Feb 2002)	
1st quarter	
CPUE [1]	24.33
95% CI [1]	22.22 – 26.45
2nd quarter	
CPUE [1]	15.96
95% CI [1]	14.93 – 17.13

3rd quarter	
CPUE [1]	34.77
95% CI [1]	26.07 – 45.61
4th quarter	
CPUE [1]	20.57
95% CI [1]	17.76 – 23.47
Full period	
CPUE [1]	21.86
95% CI [1]	20.39 – 23.47
Post regulations (3 May 2004 – 19 march 2006)	
1st quarter	
CPUE [1]	16.81
95% CI [1]	16.07 – 17.55
2nd quarter	
CPUE [1]	9.24
95% CI [1]	8.82 – 9.69
3rd quarter	
CPUE [1]	16.88
95% CI [1]	14.18 – 19.40
4th quarter	
CPUE [1]	15.34
95% CI [1]	13.86 – 16.83
Full period	
CPUE [1]	14.04
95% CI [1]	13.58 – 14.50

[1] CPUE point estimates and error intervals determined from percentile method bootstrapping at N = 1000.

[2] In the Hawaii –based longline swordfish fishery, in most years blue sharks comprise more than 90% of total shark catch, with mako and thresher sharks comprising the second and third most abundant shark species caught (Ito and Machado, 2001). Pelagic sharks comprised about 50% of the total catch composition of the Hawaii-based longline swordfish fishery (Ito and Machado, 2001).

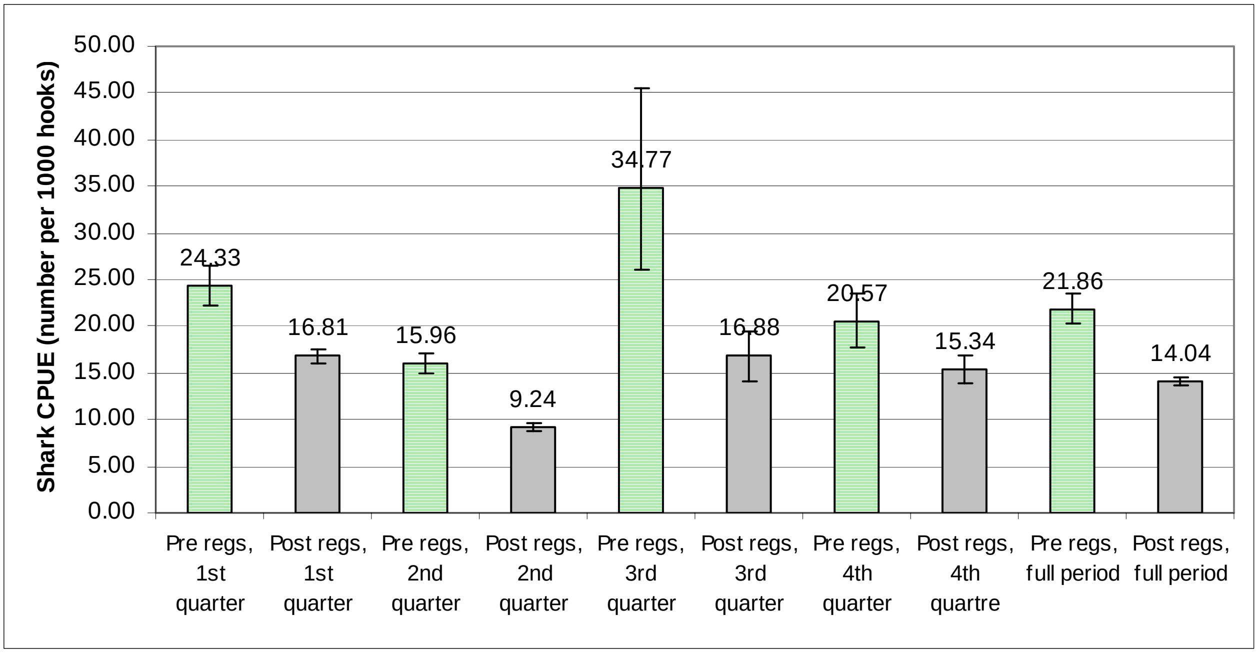


Fig. 15. Shark combined species CPUE (number per 1000 hooks) in the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

3.5. Proportion of Caught Turtles Alive vs. Dead, and Lightly Hooked vs. Deeply Hooked vs. Entangled

Table 4 summarizes the condition of turtles caught in the Hawaii longline swordfish fishery. For the period before the sea turtle regulations came into effect, of the 182 caught hardshelled turtles of known condition (known to be alive or dead), 99% (180) were alive, while 100% of the 35 caught leatherbacks of known condition were alive. One hundred percent of the 27 hardshelled turtles and 11 leatherbacks of known condition that were caught after the turtle regulations came into effect were alive. There was no significant difference in the proportion of alive vs. dead turtles for the four individual species observed captured between the two time periods before and after the sea turtle regulations came into effect (Chi-square test of heterogeneity, $X^2 = 0.0413$, DF = 4, P > 0.05).

Table 5 and Figs. 16-17 summarize the manner in which turtles were caught. Before the sea turtle regulations came into effect, for turtles where the manner of capture was known, 60% of caught hardshelled turtles ingested the hook (N = 180, 163 loggerheads). After the regulations came into effect, for turtles where the manner of capture was known, 63% of caught hardshelled turtles were lightly hooked (N = 27, all loggerheads) (Table 5, Fig. 16). Before the turtle regulations came into effect, for turtles where the manner of capture was known, 84% of leatherbacks were light hooked (N = 31), while after the turtle regulations came into effect, 100% were light hooked (N = 10) (Table 5, Fig. 17). There was no significant difference in the proportion of lightly hooked, deeply hooked, and entangled turtles for the four individual species observed captured between the two time periods before and after the sea turtle regulations came into effect (Chi-square test of heterogeneity, $X^2 = 0.8349$, DF = 8, P > 0.05).

Table 4. Condition of sea turtles caught in the Hawaii-based pelagic longline swordfish fishery for periods before and after regulations designed to reduce sea turtle interactions came into effect, 1994-2006.

	Condition of Caught Turtles				
	Alive		Dead		Unknown [a]
	No.	% of total known condition	No.	% of total known condition	No.
2 March 1994 – 20 Feb 2002					
Combined species	215	99	2	1	6
Loggerhead	164	99	2	1	1
Leatherback	35	100	0	0	2
Olive ridley	10	100	0	0	0
Green	5	100	0	0	0
Unknown hardshell	1	100	0	0	3
3 May 2004 – 19 March 2006					
Combined species	38	100	0	0	3
Loggerhead	26	100	0	0	2
Leatherback	11	100	0	0	0
Olive ridley	0		0		0
Green	0		0		0
Unknown hardshell	1	100	0	0	1

[a] Typically indicates that the caught turtle came free of the gear before getting close enough to the vessel for the observer to determine the turtle's condition.

Table 5. Proportion of turtles entangled, lightly-hooked, vs. deeply-hooked in the Hawaii-based pelagic longline swordfish fishery before and after regulations designed to reduce sea turtle interactions came into effect, 1994-2006.

	Manner of Sea Turtle Capture			
	Lightly Hooked	Deeply Hooked	Entangled [a]	Unknown [b]
2 March 1994 – 20 Feb 2002				
Combined species	95	111	5	12
Loggerhead	61	99 [c]	3	4
Leatherback	26	3	2	6
Olive ridley	3	7	0	0
Green	5	0	0	0
Unknown hardshell	0	2	0	2
3 May 2004 – 19 March 2006				

Combined species	27	6	4	4
Loggerhead	17	6	4	1
Leatherback	10	0	0	1
Olive ridley	0	0	0	0
Green	0	0	0	0
Unknown hardshell	0	0	0	2

[a] Turtles that were entangled but not hooked are recorded in this column. Turtles that were hooked and also entangled are recorded in the lightly or deeply hooked column.
[b] Turtle came free of the gear before getting close enough to the vessel for the observer to determine the turtle's condition or otherwise there was no record of the manner of the sea turtle capture.
[c] Two of these deeply hooked loggerheads were dead when hauled to the vessel.

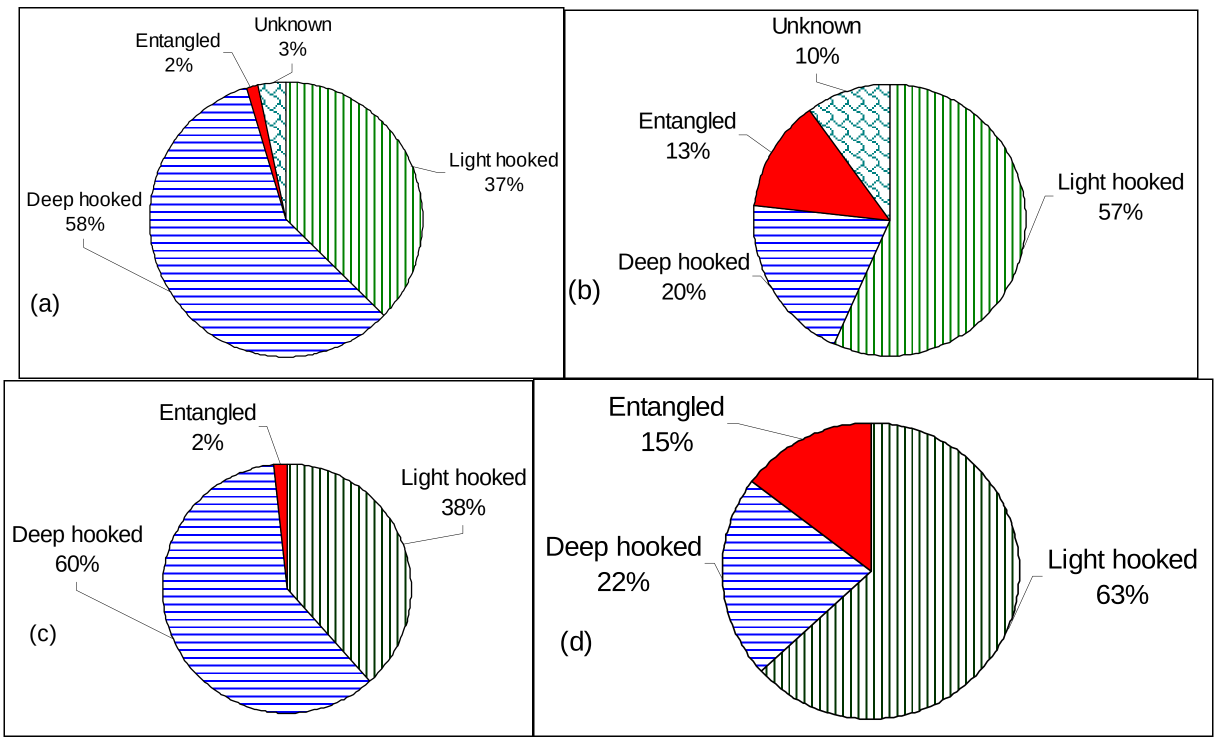
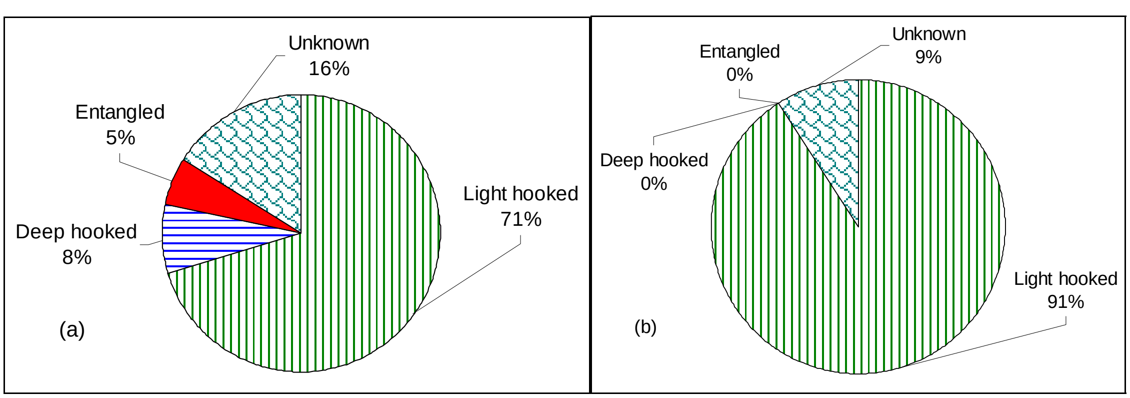


Fig. 16. Proportion of hardshelled turtles caught in the Hawaii longline swordfish fishery that were lightly hooked vs. deeply hooked vs. entangled vs. unknown (a) before and (b) after sea turtle regulations came into effect, and without the unknown proportion (c) before and (d) after the sea turtle regulations came into effect.



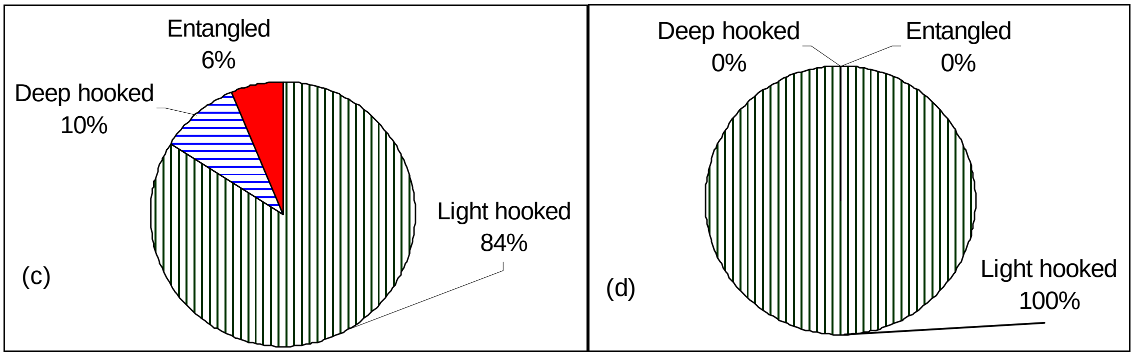


Fig. 17. Proportion of leatherback turtles caught in the Hawaii longline swordfish fishery that were lightly hooked vs. deeply hooked vs. entangled vs. unknown (a) before and (b) after sea turtle regulations came into effect, and without the unknown proportion (c) before and (d) after the sea turtle regulations came into effect.

3.6. Change in Proportion of Hooked Turtles Released with vs. without Gear Removed

Table 6 summarizes the proportion of hooked turtles that were released with vs. without terminal tackle (hook and possibly line and wire trace if used) remaining attached to the turtle for the periods before and after sea turtle regulations came into effect. For the period before the sea turtle regulations came into effect, when vessels were primarily using 9/0 J hooks, 40% of hooked turtles (combined species) were released after removing all terminal tackle (hook, line, and wire trace if used) (N = 178). After the sea turtle regulations came into effect, when vessels are required to use 18/0 circle hooks with a 10 degree offset, 67% of hooked turtles were released after the removal of all terminal tackle (N = 33). Chi-square test of heterogeneity X2 = 21.1491, DF = 8, P < 0.01, indicating that the two samples are heterogeneous and that there is a significant difference in the proportion of turtles released with terminal gear attached between the periods before vs. after the sea turtle regulations came into effect.

Table 6. Proportion of hooked turtles caught in the Hawaii-based longline swordfish fishery that were released after removal of the hook and line vs. released with the hook and line remaining attached.

	Terminal Tackle Attached or Removed to Released turtles		
	Released with no terminal tackle attached	**Released with terminal tackle attached [a]**	**Unknown [b]**
2 March 1994 – 20 Feb 2002			
Combined species	72	106	28
Loggerhead	65	89	6
Leatherback	0	10	19
Olive ridley	2	7	1
Green	5	0	0
Unknown hardshell	0	0	2
	Released with no terminal tackle attached	**Released with terminal tackle attached [a]**	**Unknown [b]**
3 May 2004 – 19 March 2006			
Combined species	22	11	0

Loggerhead	19	4	0
Leatherback	3	7	0
Olive ridley	0	0	0
Green	0	0	0
Unknown hardshell	0	0	0

[a] Terminal tackle includes a hook, and possibly also monofilament line and wire trace. Prior to 22 August 2003, managers of the Hawaii longline observer database did not input information on what type of terminal tackle, if any, was attached to released turtles. Observers have always recorded this information, thus this more detailed information is available in the hard copy observer files. For the period after the turtle regulations came into effect, all turtles that were recorded as being released with terminal tackle attached had both a hook and monofilament line attached to the turtle, none had just a hook attached.

[b] Turtle came free of the gear before getting close enough to the vessel for the observer to determine the turtle's condition or otherwise there was no record of whether or not terminal tackle was attached to the released hooked turtle.

3.7. Change in Size of Caught Turtles

Information is available on the straight carapace length of 169 hardshelled turtles, of which 155 are loggerhead turtles, and on curved carapace length for 168 hardshelled turtles of which 154 are loggerhead turtles for the period before the sea turtle regulations came into effect. Straight and curved carapace lengths are available for 26 caught loggerhead turtles for the period after the sea turtle regulations came into effect.

Table 7 and Fig. 18 summarize the differences in length of caught loggerhead sea turtles by Hawaii-based longline swordfish vessels for the periods before and after the sea turtle regulations came into effect and for just the first quarter of these two periods. For the full period, average length of caught loggerhead turtles was greater after the sea turtle regulations came into effect than before the regulations came into effect when comparing the straight carapace length and curved carapace length of loggerheads that were (i) mouth hooked and ingested hooks, (ii) foul-hooked in the body or entangled, or (iii) all caught loggerheads, however differences in length were not significantly different based on overlapping 95% confidence intervals derived from percentile method bootstrapping at N = 1000 (Table 7, Fig. 18). For just the first quarter, for all caught loggerheads and for loggerheads that were mouth hooked and ingested hooks, again the average length of caught loggerheads for the same three categories was greater during the period after the regulations came into effect, but the differences were not significant based on overlapping 95% confidence intervals derived from percentile method bootstrapping at N = 1000 (Table 7).

We included the comparison of the lengths of loggerhead turtles caught during only the first quarter of the two time periods because, in the period before the turtle regulations, 58% of loggerhead turtles were caught in the first quarter, while 86% were caught in the first quarter during the period after the regulations came into effect. If there are significantly larger or smaller loggerhead turtles at the Hawaii longline swordfish fishing grounds during January-March relative to other seasons, because a higher proportion of loggerheads were caught in the first quarter during the period after the turtle regulations came into effect, this could result in a significantly different mean length of turtles during the two periods. Comparing lengths of turtles for just the first quarter eliminates any possible seasonal effect occurring during this quarter. Too few loggerheads were caught in the other quarters during the period after regulations came into effect to conduct an accurate comparison of loggerhead lengths.

Table 7. Straight carapace length of loggerhead sea turtles caught by the Hawaii-based longline swordfish fishery before and after sea turtle regulations came into effect.

	Loggerhead mean length (cm), pre sea turtle regulations			Loggerhead mean length (cm), post sea turtle regulations		
	Body foul-hooked or entangled	Mouth hooked or ingested hook	All caught loggerheads	Body foul-hooked or entangled	Mouth hooked or ingested hook	All caught loggerheads
Full Period						
Straight carapace length						
Mean	51.1	56.8	56.4	59.5	62.1	60.9
N	13	142	155	12	14	26
Standard deviation of the mean	2.6	0.8	0.8	2.9	2.6	1.9
95% CI[1]	45.1 – 57.4	55.2 – 58.4	55.0 – 58.0	55.1 – 66.0	57.1 – 66.8	57.5 – 64.6
Curved carapace length						
Mean	55.6	61.9	61.3	64.7	67.3	66.1
N	13	141	154	12	14	126
Standard deviation of the mean	2.5	0.9	0.8	2.9	2.5	1.9
95% CI[1]	49.9 – 61.5	60.1 – 63.6	59.8 – 62.9	60.0 – 70.6	62.5 – 72.8	62.6 – 69.9
First quarter						
Straight carapace length						
Mean	54.75	56.64	56.47	59.54	62.14	60.78
N	8	83	91	12	11	23
Standard deviation of the mean	3.6	1.1	1.0	2.9	3.3	2.1
95% CI[1]	48.13 – 61.44	54.61 – 58.63	54.46 – 58.44	55.00 – 65.58	55.91 – 68.50	56.70 – 65.00
Curved carapace length						
Mean	58.63	61.55	61.29	64.71	67.64	66.11
N	8	83	91	12	11	23
Standard deviation of the mean	3.5	1.1	1.0	2.9	3.2	2.1
95% CI[1]	52.19 – 65.25	59.50 – 63.73	59.34 – 63.32	60.29 – 70.50	61.86 – 73.77	62.37 – 70.41

[1] Nonparametric 95% confidence intervals derived from percentile method bootstrapping at N = 1000.

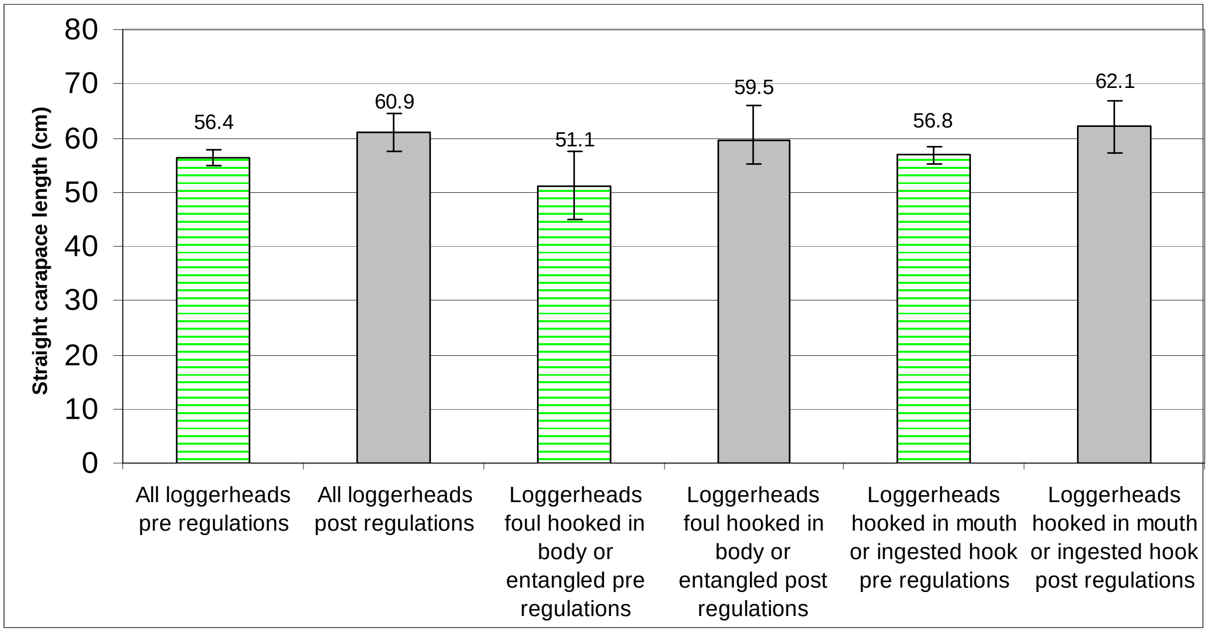


Fig. 18. Straight carapace length of loggerhead sea turtles caught in the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

3.8. Turtle Catch Rates in 2005 and 2006

Table 8 presents sea turtle CPUE by quarter for 2005 and 2006, and Fig. 19 presents sea turtle CPUE for the first quarters of 2005 and 2006. There was no significant difference in CPUE for combined turtle species, loggerheads, or leatherbacks between the first quarters of 2005 and 2006 based on overlapping 95% confidence intervals derived from percentile method bootstrapping at N = 1000. Effort in the first quarter of 2006 was 48% higher than in 2005. The higher fishing effort during the first quarter of 2006 relative to 2005 is the cause of the higher number of loggerhead captures.

Table 8. Sea turtle capture rates by the Hawaii longline swordfish fishery in 2005 and 2006. The swordfish fishery was closed ion 19 March in 2006, when a total of 15 loggerheads and 2 unknown hardshelled sea turtles were caught, thus only effort and turtle captures are reported for the first quarter of 2006.

Observed turtle captures, effort, and CPUE [1]	Period				
	2005				2006
	1st quarter	2nd quarter	3rd quarter	4th quarter	1st quarter
Observed Turtle Captures					
Combined species	11	5	0	4	19
Loggerhead	9	0	0	3	15
Leatherback	2	5	0	1	2
Olive ridley	0	0	0	0	0
Green	0	0	0	0	0
Unknown	0	0	0	0	2 [2]

Effort					
Number hooks observed	457,166	715,470	45,194	136,872	676,709
Turtle CPUE					
Combined species turtle CPUE (number captured per 1000 hooks)	0.0241	0.0070	0.000	0.0292	0.0281
Combined species CPUE 95% CI	0.0109 – 0.0397	0.0014 – 0.0139	0.000 - 0.000	0.0071 – 0.0597	0.0160 – 0.0416
Loggerhead CPUE (number captured per 1000 hooks)	0.0197	0.0000	0.0000	0.0219	0.0222
Loggerhead CPUE 95% CI	0.0087 – 0.0328	0.000 - 0.000	0.000 - 0.000	0.0000 – 0.0508	0.0117 – 0.0343
Leatherback CPUE (number captured per 1000 hooks)	0.0044	0.007	0.000	0.0073	0.0030
Leatherback CPUE 95% CI	0.0000 – 0.0111	0.0014 – 0.0127	0.000 - 0.000	0.0000 – 0.0223	0.0000 – 0.0074

[1] CPUE point estimates and error intervals determined from percentile method bootstrapping at N = 1000.

[2] Conservatively assumed to be loggerhead turtles.

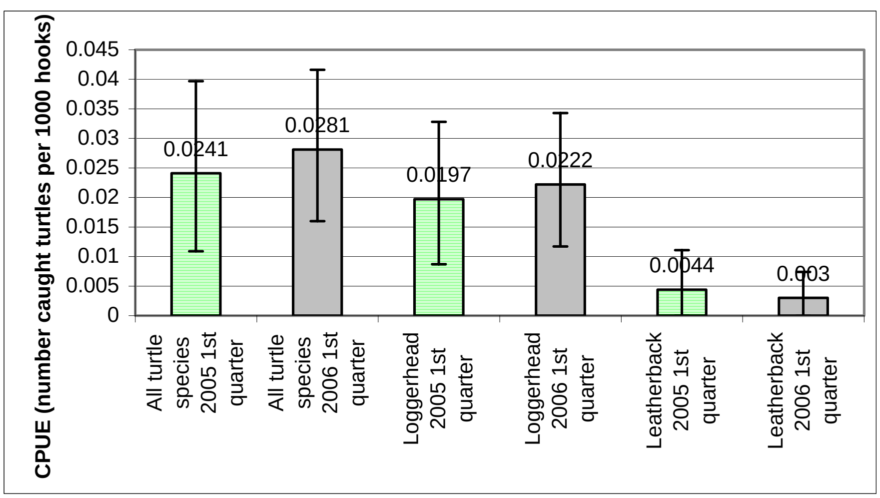


Fig. 19. Sea turtle capture rates (captures per 1000 hooks) in the Hawaii-based pelagic longline swordfish fishery for combined turtle species, loggerhead turtles, and

leatherback turtles for first quarters of 2005 and 2006. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

3.9. Spatial and Temporal Closures

Fig. 20 compares CPUE of swordfish and combined species of sea turtles by quarter for the full study period. Because disproportionately little swordfish effort has occurred during the latter half of the year, with only 5% and 14% of effort in the third and fourth quarters, respectively, error intervals around these CPUE point estimates are relatively large. Turtle CPUE was significantly lower in the second quarter than the other three quarters. There was no significant difference in turtle CPUE for the first, third, and fourth quarters, based on non-overlapping nonparametric 95% CIs derived from percentile method bootstrapping at N = 1000, with the highest turtle CPUE point estimate occurring in the third quarter, and second highest in the fourth quarter. Swordfish CPUE was significantly different for each quarter. Swordfish CPUE was significantly lower than all other quarters in the third quarter. The first and fourth quarters had significantly highest and second highest swordfish CPUE, respectively.

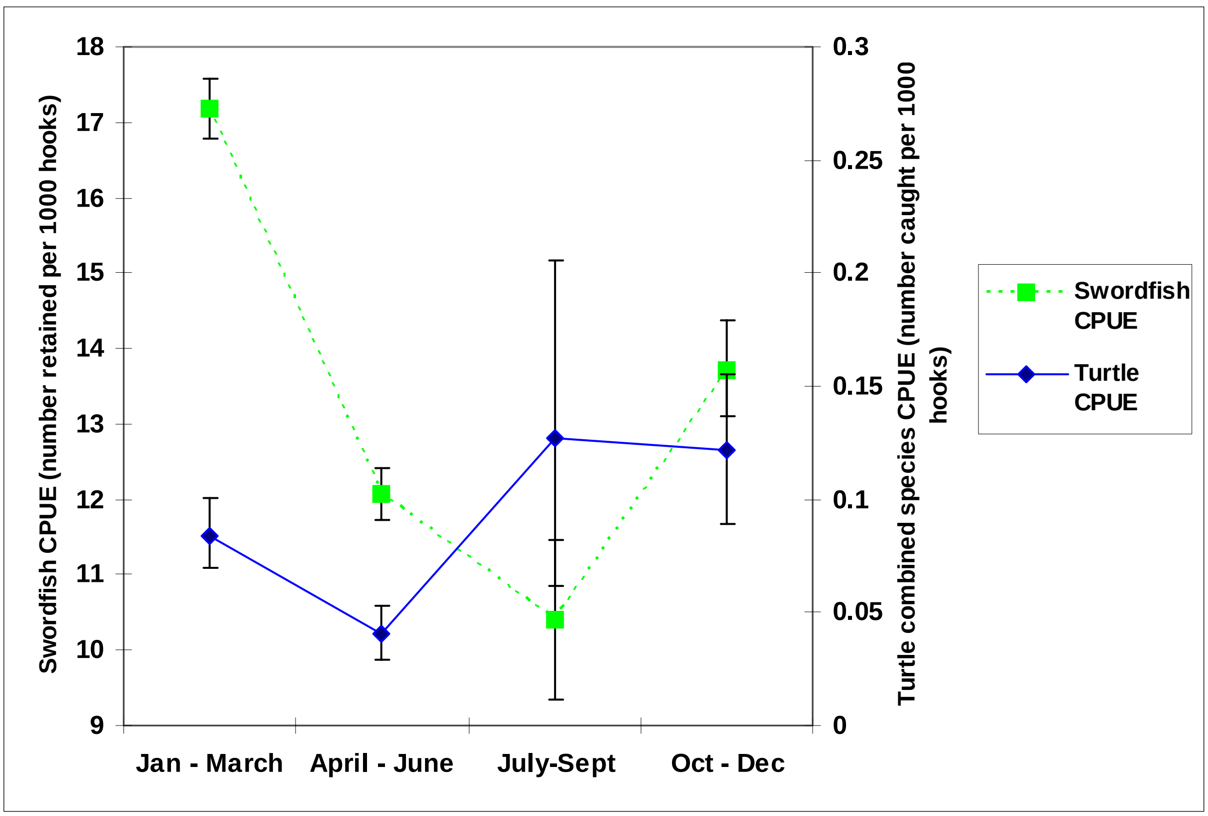


Fig. 20. CPUE of swordfish and sea turtles combined species in the Hawaii-based longline swordfish fishery by quarter, 1994 – 2006.

Fig. 21a shows the location of both Hawaii-based longline swordfish effort and location of turtle captures and Fig. 21b shows the spatial distribution of turtle CPUE for the full period that the fishery has been observed from 1994-2006. There were two 5 x 5 degree cells with relatively high turtle capture rates that had a relatively small proportion of fishing effort. These two areas are from 35-40 degrees N. latitude, and 160-165 and 165-170 degrees W. longitude. In the area between 35-40 degrees N. latitude, 160-165 degrees W. longitude, 15 turtles were captured and 23,565 hooks were set, giving a turtle CPUE of 0.637 turtles per 1000 hooks. In the area between 35-40 degrees N. latitude, 165-170 degrees W. longitude, eight turtles were captured and 26,041 hooks were set, giving a turtle CPUE of 0.307 turtles per 1000 hooks. The turtle catch rates of these areas are higher than any of the observed turtle catch rates by quarter, and are an order of magnitude higher than the observed turtle capture rate for the full period of 0.0767 turtle captures per 1000 hooks (Table 1). The turtle captures in these two areas represent 8.7 % of the total observed 264 caught turtles and 1.4% of the total observed effort made by the Hawaii-based longline swordfish fishery.

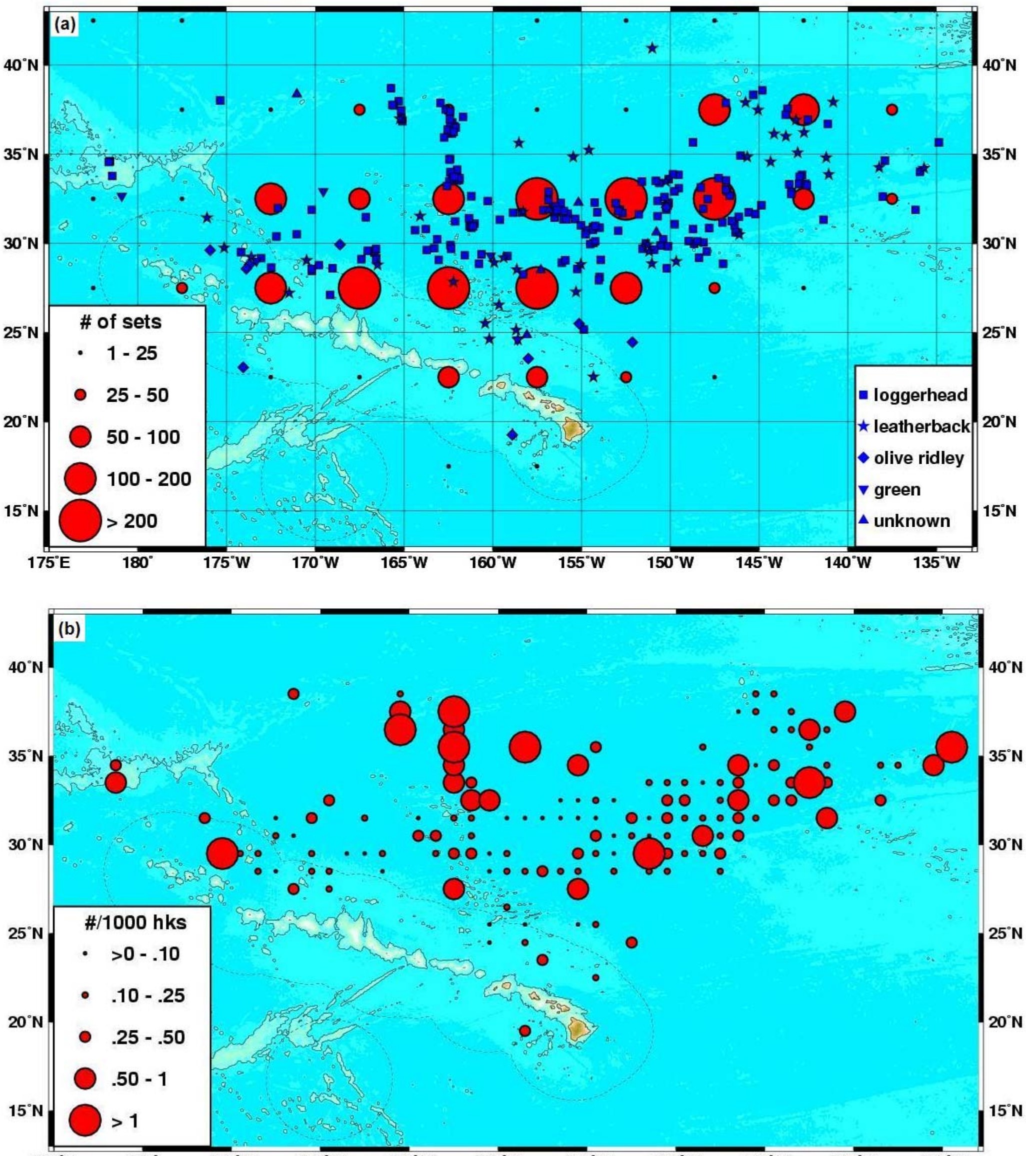


Fig. 21. (a) Location of Hawaii-based longline swordfish sets (N = 4,262) at 5.0 degree resolution and location of observed turtle captures randomly 'jittered' by +/- 2.5 degrees (N = 264), and (b) spatial distribution of turtle CPUE (number of turtle captures per 1000 hooks) at 1.0 degree resolution, also 'jittered' by +/- 2.5 degrees, 1994-2006.

3.10. Hook Position of Caught Turtles

During the period before the sea turtle regulations came into effect, the number of hooks set to target swordfish were 41,679; 891,895; 301,373; 27,496; and 614 for sets with 3, 4, 5, 6, and 7 hooks per basket, respectively. During the period after the turtle regulations came into effect, the number of hooks set to target swordfish were 21,570; 1,678,307; 414,218; 31,621; and 3,717 for sets with 3, 4, 5, 6, and 7 hooks per basket, respectively. Vessels primarily set 4 hooks per basket (between floats): 75% of hooks set to target swordfish by the Hawaii-based longline fleet were in baskets containing 4 hooks. Twenty one percent of hooks set by Hawaii longline vessels to target swordfish were in baskets containing 5 hooks.

Based on overlapping 95% confidence intervals derived from percentile method bootstrapping at N = 1000, there was no significant difference between catch rates of sea turtles combined species, loggerheads, leatherbacks, and hardshelled turtle combined species on hooks in a basket that are not located next to floats vs. hooks located immediately next to floats, and there was nominal differences between sea turtle CPUE point estimates for the two different categories of hooks (Table 9, Fig. 22).

Table 9. CPUE of sea turtles caught in Hawaii-based longline swordfish sets on hooks next to float lines versus on hooks not located next to float lines. Nonparametric 95% confidence intervals derived from percentile method bootstrapping at N = 1000 are reported.

	No. of hooks per basket					
	3	**4**	**5**	**6**	**7**	**Combined**
Number of hooks						
Next to floats	42,166	1,285,101	286,236	19,706	1,237	1,634,446
Not next to floats	21,083	1,285,101	429,355	39,411	3,094	1,778,044
CPUE (no. per 1000 hooks) and no. of caught turtles combined species						
Hooks next to floats CPUE (no.)	0.07 (3)	0.08 (102)	0.06 (16)	0 (0)	0 (0)	0.07 (121)
95% CI	0.00 – 0.17	0.07 – 0.09	0.03 – 0.08	0.00 – 0.00	0.00 – 0.00	0.06 – 0.09
Hooks not next to floats CPUE (no.)	0.14 (3)	0.06 (78)	0.11 (48)	0.08 (3)	0 (0)	0.07 (132)
95% CI	0.00 – 0.33	0.05 – 0.08	0.08 – 0.14	0.00 – 0.18	0.00 – 0.00	0.06 – 0.09
CPUE (no. per 1000 hooks) and no. of loggerheads						
Hooks next to floats CPUE (no.)	0.02 (1)	0.06 (76)	0.04 (12)	0 (0)	0 (0)	0.055 (89)
95% CI	0.00 – 0.07	0.05 – 0.07	0.02 – 0.07	0.00 – 0.00	0.00 – 0.00	0.05 – 0.06
Hooks not next to floats CPUE (no.)	0.09 (2)	0.04 (54)	0.10 (41)	0.05 (2)	0 (0)	0.056 (99)
95% CI	0.00 – 0.24	0.03 – 0.05	0.07 – 0.12	0.00 – 0.13	0.00 – 0.00	0.05 – 0.07

CPUE (no. per 1000 hooks) and no. of leatherbacks						
Hooks next to floats CPUE (no.)	0.05 (2)	0.02 (20)	0.01 (2)	0 (0)	0 (0)	0.01 (24)
95% CI	0.00 – 0.12	0.01 – 0.03	0.00 – 0.02	0.00 – 0.00	0.00 – 0.00	0.01 – 0.02
Hooks not next to floats CPUE (no.)	0.05 (1)	0.01 (15)	0.01 (4)	0.03 (1)	0 (0)	0.01 (21)
95% CI	0.00 – 0.14	0.01 – 0.02	0.00 – 0.02	0.00 – 0.08	0.00 – 0.00	0.01 – 0.02
CPUE (no. per 1000 hooks) and no. of combined hardshelled turtles1						
Hooks next to floats CPUE (no.)	0.02 (1)	0.06 (82)	0.05 (14)	0 (0)	0 (0)	0.06 (97)
95% CI	0.00 – 0.07	0.05 – 0.08	0.03 – 0.07	0.00 – 0.00	0.00 – 0.00	0.05 – 0.07
Hooks not next to floats CPUE (no.)	0.09 (2)	0.05 (63)	0.10 (44)	0.05 (2)	0 (0)	0.06 (111)
95% CI	0.00 – 0.24	0.04 – 0.06	0.07 – 0.13	0.00 – 0.13	0.00 – 0.00	0.05 – 0.07

[1] Loggerhead, olive ridley, green, and unidentified hardshelled turtles.

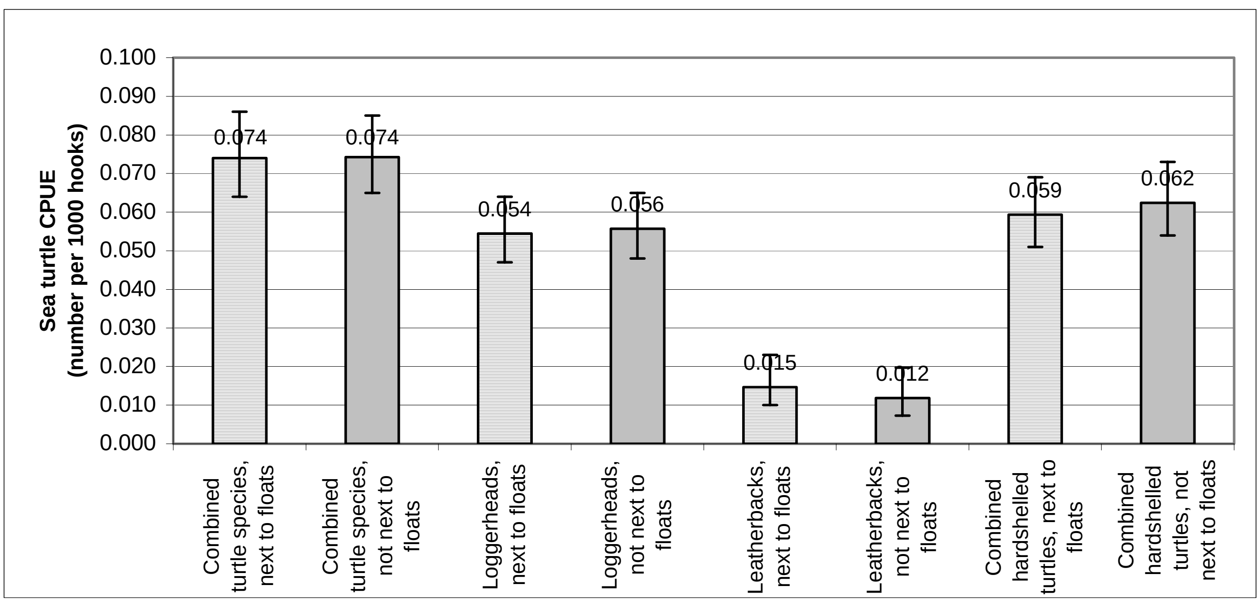


Fig. 22. CPUE for sea turtles caught on hooks located immediately next to float lines vs. on hooks located in between the hooks located next to float lines, Hawaii-based longline swordfish fishery. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

3.11. Hook Position of Retained Fish

The catch rate of retained fish combined species, retained swordfish and retained tunas are slightly higher on hooks in a basket that are not located next to floats vs. hooks located immediately next to floats (Table 10, Fig. 23). The catch rate of combined retained mahimahi, opah, and wahoo is higher on hooks located closest to floats vs. hooks not located immediately adjacent to floats (Table 10, Fig. 23). Differences in CPUE for all retained fish and combined tuna species were not significantly different based on overlapping 95% confidence intervals derived from percentile method bootstrapping at N = 1000, while differences in CPUE for swordfish and combined mahimahi, opah, and wahoo were significantly different based on non-overlapping 95% confidence intervals (Table 10).

Table 10. CPUE of retained fish caught in Hawaii-based pelagic longline swordfish sets on hooks next to float lines versus on hooks not located next to float lines. Nonparametric 95% confidence intervals derived from percentile method bootstrapping at N = 1000 are reported.

	No. of hooks per basket					
	3	**4**	**5**	**6**	**7**	**Combined**
Number of hooks						
Next to floats	42,166	1,285,101	286,236	19,706	1,237	1,634,446
Not next to floats	21,083	1,285,101	429,355	39,411	3,094	1,778,044
Retained fish combined species CPUE (no. per 1000 hooks) and number						
Hooks next to floats CPUE (no.)	8.8 (370)	15.2 (19,511)	12.1 (3,455)	11.2 (221)	20.2 (25)	14.4 (23,582)
95% CI	7.8 - 9.6	15.1 – 15.4	11.8 – 12.4	9.7 – 12.6	12.9 – 29.1	14.3 – 14.6
Hooks not next to floats CPUE (no.)	8.1 (170)	15.1 (19,440)	13.3 (5,706)	8.6 (338)	12.9 (40)	14.5 (25,694)
95% CI	6.8 – 9.2	15.0 – 15.3	13.0 – 13.6	7.6 – 9.5	9.0 – 17.1	14.3 – 14.6
Swordfish CPUE (no. per 1000 hooks) and number						
Hooks next to floats CPUE (no.)	4.8 (203)	9.6 (12,394)	8.3 (2,386)	7.8 (154)	12.1 (15)	9.3 (15,152)
95% CI	4.2 – 5.5	9.5 – 9.8	8.0 – 8.6	6.6 – 8.9	6.5 – 17.8	9.2 – 9.4
Hooks not next to floats CPUE (no.)	4.6 (97)	10.1 (13,013)	9.5 (4,065)	6.0 (237)	5.8 (18)	9.8 (17,430)
95% CI	3.7 – 5.5	10.0 – 10.3	9.2 – 9.7	5.2 – 6.8	3.2 – 8.4	9.7 – 9.9
Tuna species[1] CPUE (no. per 1000 hooks) and number						
Hooks next to floats CPUE (no.)	0.62 (26)	1.5 (1,954)	1.2 (336)	2.0 (39)	0.81 (1)	1.4 (2,356)
95% CI	0.38 –	1.5 – 1.6	1.0 – 1.3	1.4 – 2.6	7.8×10^{-7} – 2.4	1.38 – 1.50

	0.85					
Hooks not next to floats CPUE (no.)	0.81 (17)	1.6 (2,085)	1.3 (553)	1.6 (65)	1.9 (6)	1.5 (2,726)
95% CI	0.43 – 1.2	1.6 – 1.7	1.2 – 1.4	1.3 – 2.1	0.65 – 3.6	1.47 – 1.59
Mahimahi, opah, and wahoo CPUE (no. per 1000 hooks) and number						
Hooks next to floats CPUE (no.)	1.2 (51)	2.4 (3,089)	1.6 (469)	1.1 (22)	2.4 (3)	2.2 (3,634)
95% CI	0.90 – 1.6	2.3 – 2.5	1.5 – 1.8	0.66 – 1.6	4.6×10^{-6} – 5.7	2.2 – 2.3
Hooks not next to floats CPUE (no.)	0.71 (15)	1.7 (2,181)	1.3 (539)	0.38 (15)	0.32 (1)	1.5 (2,751)
95% CI	0.38 – 1.1	1.6 – 1.8	1.1 – 1.4	0.20 – 0.58	2.3×10^{-7} – 0.97	1.5 – 1.6

[1] Albacore, bigeye, skipjack, and yellowfin tunas.

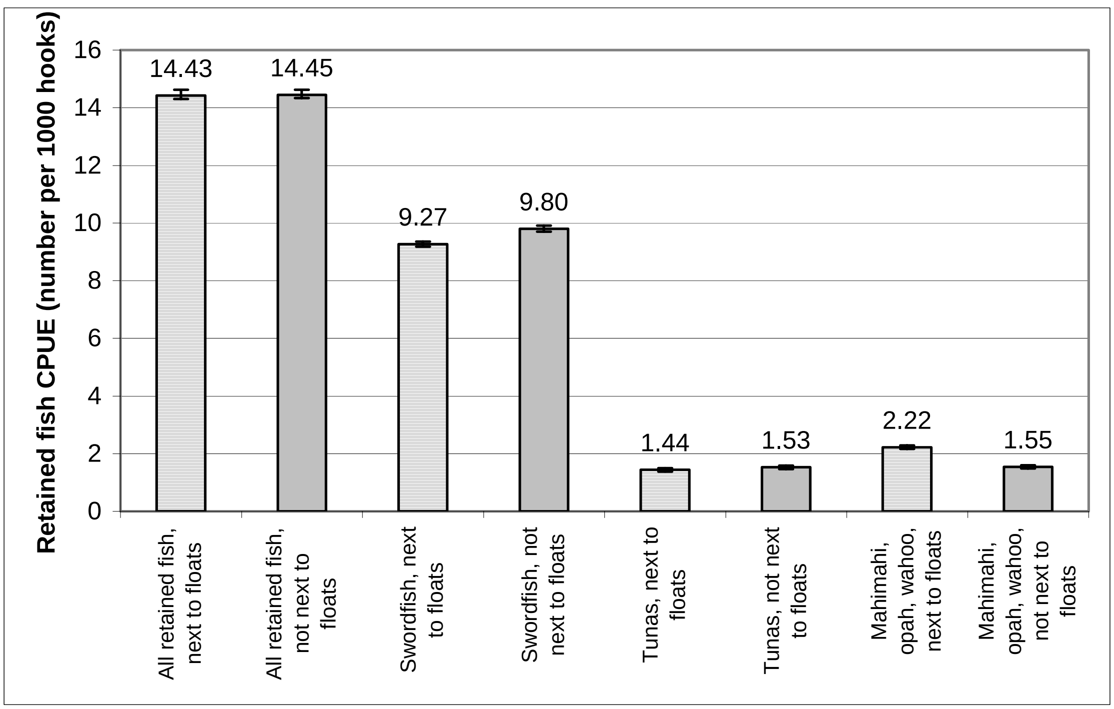


Fig. 23. CPUE for retained fish caught on hooks located immediately next to float lines vs. on hooks located in between the hooks located next to float lines, Hawaii-based longline swordfish fishery. Error bars are boostrapped (N = 1000) 95% nonparametric confidence intervals.

4. DISCUSSION

4.1. Confounding Factors

The existence of confounding factors prevents definitive conclusions regarding the single factor effects on turtle and fish interactions for the periods before vs. after the Hawaii sea turtle regulations came into effect. In addition to the change in fishing hook and bait by the Hawaii longline swordfish fishery required by the sea turtle regulations, several other factors may contribute to explaining the observed changes in turtle and fish interactions between the periods before vs. after the turtle regulations came into effect. The Hawaii longline swordfish fishery has been required to employ methods to reduce seabird bycatch since 12 June 2001 (50 CFR 660.35, U.S. National Marine Fisheries Service, 2002). These seabird avoidance regulations include requirements for swordfish-targeting vessels to night set (gear setting must be initiated at least one hour after local sunset) and dye bait blue, which are two changes that possibly could affect sea turtle and fish capture rates. Prior to this rule coming into effect, swordfish vessels did not dye bait blue and the mean time for initiating setting was at 18:29:45 (+/- 2.4 minutes standard deviation of the mean, N = 1615 sets). After the night setting requirement came into effect, the mean time for initiating sets by swordfish vessels was at 19:45:31 (+/- 1.4 minutes standard deviation of the mean, N = 2646 sets), 75 minutes and 46 seconds later than for the period before the night setting requirement came into effect. Hawaii-based swordfish vessels were subject to the night setting and blue bait requirements for the entire period after the sea turtle regulations came into effect, and for the last eight months of the period before the sea turtle regulations came into effect.

Furthermore, it is possible that Hawaii-based swordfish vessels may have made voluntary, currently unknown, changes to their fishing gear and methods as a result of the sea turtle regulations. For instance, the sea turtle regulations create a cap on longline swordfish effort, limiting the annual number of swordfish sets (U.S. National Marine Fisheries Service 2004a). One result of this limit on the number of swordfish sets may be that swordfish vessels have increased the number of hooks in a basket or total number of baskets per set in order to increase their effort. An increase in the number of hooks per basket could increase the depth of baited hooks, which could possibly contribute to reducing turtle interaction rates (Gilman et al., 2006a).

For the period after the turtle regulations came into effect, fishers have had an increased incentive to conceal caught turtles from onboard observers, such as dropping branch lines containing caught turtles before an observer is able to notice, who might be busy measuring caught fish on deck and not continually watching the gear retrieval off the bulwark. This is a documented problem for seabird bycatch where seabird catch rates recorded on fishing vessels from observations of dead birds hauled aboard are known to be underestimates, in part, because there is unobserved discarding of incidentally caught seabirds by crew (Brothers 1991; Gales *et al.* 1998; Gilman *et al.* 2005).

Another possible confounding factor is variability in turtle abundance at fishing grounds and variability in the temporal distribution of effort. Information on sea turtle abundance around fishing vessels is not available This prevents determining the effect of turtle abundance on capture rates, such as by normalizing capture rates for turtle abundance (Gilman et al., 2003). Turtle abundance is likely to change by area for each season of different years, as turtle abundance is correlated with the location of large-scale oceanographic features and short-lived hydrographic features such as eddies and fronts (Hyrenbach *et al.* 2000; Kleiber and Boggs 2000; Polovina et al., 2000). Also, changes in turtle population sizes may be contributing to observed changes in turtle capture rates. While the status of most Pacific leatherback populations is not well understood, there are indications of a long term decline in leatherback nesting in the western Pacific (Spotila *et al*. 2000; Kamezaki *et al*. 2003; Limpus and Limpus 2003; Dutton et al., In Press; Hitipeuw et al., In

Press). Pacific loggerhead nesting populations have been observed to decline 50-90% over the past 50 years (Hatase et al., 2002; Kamezaki et al., 2003).

Analysis of the location of Hawaii-based longline swordfish effort by quarter for the periods before vs. after the sea turtle regulations came into effect generally indicate that there was no substantial differences in the location of effort by season for these two periods. Additional research could be conducted to attempt to identify the relative influence of various known confounding factors on observed differences between the two study periods, for instance, by modeling time and area variations of oceanographic fronts.

4.2. Change in Turtle CPUE

Sea turtle capture rates were an order of magnitude lower for the period after the sea turtle regulations came into effect relative to the period before the sea turtle regulations. There were also significantly lower turtle catch rates for combined turtle species and individual species for each quarter of each year in the period after the sea turtle regulations came into effect compared to the same quarter of each year before the regulations came into effect, except for leatherback turtle catch rates during the 1st quarter for which the difference was not significant. Thus, differences in temporal distribution of fishing effort between the two periods is not likely a large factor in explaining the differences in turtle CPUE between the two time periods. While it is not possible to determine single factor effects on observed changes in turtle catch rates, these observed reductions in turtle catch rates are consistent with results from controlled experiments on the effects of switching from a J or Japan hook to a wider circle hook and switching from using squid to fish for bait (Bolten and Bjorndal, 2005; Watson et al., 2005; Largacha et al., 2005; Gilman et al., 2006a). The percent reductions in loggerhead and leatherback capture rates observed in this study are generally consistent with the results of Watson et al., (2005). Watson et al. (2005) found that 10 degree offset 18/0 circle hooks with mackerel bait significantly reduced loggerhead and leatherback captures by 88% and 63% respectively, compared to conventionally used 9/0 J hooks with squid bait in the U.S. Atlantic pelagic longline swordfish fleet. The Watson et al. (2005), Bolten and Bjorndal (2005), and Largacha et al. (2005) studies were controlled experiments, thus limiting the factors that explain observed differences in turtle interactions.

Results reported here are from the analysis of observer data, where numerous confounding factors may have influenced observed differences in turtle capture rates, including differences in turtle abundance around fishing gear between the periods before and after the turtle regulations came into effect. Other factors that may have contributed to observed differences in sea turtle capture rates between the two time periods is the change in June 2001 to night set and dye bait blue. While research to date has shown that blue dyed bait does not significantly alter sea turtle capture rates, research indicates that the change in timing of setting and hauling to comply with the night setting requirement may have affected turtle capture rates (Bolten and Bjorndal, 2003; Watson *et al*. 2004; Gilman et al., 2006a). Bolten and Bjorndal (2003) documented a significant increase in loggerhead capture rate with increased length of daytime line hauling while research with hook timers indicates that leatherbacks are hooked more frequently at night (Watson *et al*. 2004). Alternatively, the later time of day of initiating gear setting might have contributed to causing a decrease in turtle CPUE if turtles are primarily caught as the gear travels through the water column during setting and hauling and not during the gear soak.

4.3. Proportion of Caught Turtles Lightly Hooked vs. Deeply Hooked vs. Entangled

While it is not possible to determine single factor effects on observed changes in turtle interactions, this observed reduction in proportion of turtle deep hooking is consistent with results from controlled experiments on the effects of switching from a J or Japan tuna hook to a circle hook (Bolten and Bjorndal, 2005; Watson et al., 2005; Largacha et al., 2005; Gilman et al., 2006a). The reduction in the proportion of hooked hardshelled turtles and increase in the proportion that were entangled indicates that turtles caught in the Hawaii swordfish fishery are experiencing reduced injuries as a result of interactions with longline gear, assuming that entangled turtles are likely released in better condition than hooked turtles. Also, U.S. fishery management authorities hypothesize that mouth-hooked turtles have higher post-hooking survival prospects than more deeply hooked turtles, where fully ingested hooks are likely to result in eventual mortality (Epperly and Boggs, 2004). Current practice for turtle mortality estimates in longline fisheries by U.S. fishery management protected resources authorities considers whether or not gear is removed from a turtle before release (U.S. National Marine Fisheries Service 2004b), which is more readily accomplished with lightly-hooked versus more deeply hooked turtles. Post-release-mortality of loggerhead and leatherback turtles is estimated to be 40% and 32%, respectively, resulting from interactions with U.S. North Atlantic pelagic longline swordfish gear using J hooks, assuming that fishers remove gear from and release light-hooked turtles and that deeper hooking causes greater mortality (U.S. National Marine Fisheries Service 2004b). Chaloupka *et al*. (2004) found light hooked loggerhead turtles had significantly longer time-to-failure of satellite transmitters versus deep hooked turtles within 90 days of release. But the cause of transmitter failures is not known, preventing reliable estimates of mortality based on these observations (Swimmer *et al*. 2002; Chaloupka *et al*. 2004). Also, none of the turtles released in the light-hooked sample included turtles released with a hook retained in the mouth, and there was a small sample size (40 turtles, 27 deep hooked and 13 light hooked) (Chaloupka *et al*. 2004; Parker *et al*. In Press).

4.4. Comparison of Individual Vessel's Swordfish and Turtle Catch Rates

A comparison of individual vessel's swordfish and sea turtle CPUE reveals that there are several vessels with turtle catch rates far above the mean but whose swordfish catch rates are not relatively high, and there are several vessels with high swordfish catch rates and low turtle catch rates. There was no significant correlation between swordfish and turtle CPUE, indicating that vessels with high swordfish catch rates do not necessarily have high turtle catch rates, and a vessel with a high turtle catch rate may not have a high swordfish catch rate. The maximum number of turtles caught by a single vessel was 23. The vessel that caught 23 turtles had a sea turtle capture rate of 0.36 turtle captures per 1000 hooks, which is 3.8 times the average turtle CPUE of swordfish-targeting vessels, while its swordfish catch rate is slightly below the mean for the fleet. This one vessel, representing 1.5% of the number of vessels participating in the fishery, caught 9% of the total turtles caught by the fleet. Another vessel had a swordfish catch rate that is 1.8 times higher than the fleet's average and a turtle catch rate that is half the fleet's average. There are three vessels with swordfish catch rates $\geq$ 30% of the mean for the fleet that also have turtle catch rates below the mean rate for the fleet (Fig. 14). It is a research priority to investigate differences between vessels with high turtle CPUE and low swordfish CPUE to those with low turtle CPUE and high swordfish CPUE to possibly identify new strategies to reduce turtle catch rates without compromising economic viability. Additional research can be conducted to determine if the vessels with the relatively high turtle catch rates have had higher fishing effort during periods when turtle catch rates are highest, or if they employ different fishing methods and gear compared to vessels with relatively low turtle catch rates.

4.5. Rarity of Turtle Captures

Turtle captures are an extremely rare event: Because 24% of the sets where a turtle was caught were in consecutive sets where $\geq$ 1 turtle was caught per set, and because 23% of turtles observed caught were caught in clusters of $\geq$ 1 turtle per set, this indicates that there may be a higher probability of catching turtles in sets following a set where a turtle was caught if they are made at the same location. This indicates that moving vessel position before making another set after a turtle is caught, and employing other methods to avoid real time turtle bycatch hotspots, such as fleet communication programs, could contribute to reducing turtle catch rates in the Hawaii-based longline swordfish fishery (Gilman et al., 2006b).

4.6. Catch Rate of Retained Fish

Observed differences in swordfish and tuna catch rates for the periods when a 9/0 J hook with squid bait was in use vs. the period when a 10 degree offset 18/0 circle hook with fish bait was in use are consistent with results from a controlled experiment in the U.S. North Atlantic longline swordfish fishery (Watson et al., 2005). In the period after sea turtle regulations came into effect, swordfish CPUE was significantly higher by 16.0% while combined tuna species and combined mahimahi, opah, and wahoo CPUE was significantly lower by 50.0% and 34.1%, respectively. The CPUE of combined retained fish for the two periods was not significantly different, and was 2.6% lower in the second period. When analyzed by quarter, differences in CPUE of retained fish were generally consistent with results for the full period, except for swordfish. Results on changes in retained fish CPUE need to be considered with caution because the fishing effort was distributed very differently by quarter for the two periods before and after the turtle regulations came into effect. For example, if there had been more fishing effort during the fourth quarter and less during the first quarter for the period after the regulations came into effect, because swordfish CPUE was significantly higher by 23% during the first quarter but significantly lower by 27% during the fourth quarter, the change in swordfish CPUE for the full period could have resulted in an overall reduction after the regulations came into effect.

4.7. Catch Rate of Sharks

There was a significant decrease in shark CPUE from the period before to after the sea turtle regulations came into effect. This is likely due to the change from using squid to mackerel for bait. Research in the Azores longline swordfish and blue shark fishery found that when non-offset 16/0 circle hooks were used, there was a significantly higher blue shark CPUE than when fishing with a non-offset 9/0 J hook in a 2000 study when blue sharks were not being targeted due to low market demand (Bolten and Bjorndal 2002). In a 2001 study in the Azores fishery, when blue sharks were being targeted, fishing with non-offset 16/0 and non-offset 18/0 circle hooks caught significantly more blue sharks than when fishing with a non-offset 9/0 J hook (Bolten and Bjorndal 2003). Thus, in both Azores studies, fishing with a circle hook results in a significantly higher blue shark catch rate when compared to fishing with a J hook. A study conducted in the U.S. North Atlantic longline swordfish fishery found that use of a non-offset or 10 degree offset 18/0 circle hook with squid bait resulted in a small but significant increase in blue shark CPUE (8% and 9% increases, respectively) compared to fishing with a 9/0 J hook with squid (Watson et al., 2005). Watson et al. (2005) also found that fishing with a 10 degree offset 18/0 circle hook with mackerel bait and fishing with a 9/0 J hook with mackerel bait resulted in a significant and large reduction in blue shark CPUE by 31% and 40%, respectively, compared to fishing with a 9/0 J hook with squid. Thus, results from the Azores and U.S. North Atlantic longline fisheries indicate that it was likely the change in bait type that caused the decrease in shark CPUE in the Hawaii-based longline swordfish fishery. However, the Hawaii swordfish fleet's change to dye bait blue, change in timing of setting and hauling as a result of the requirement for night setting, and other differences between the two time periods before vs. after the sea turtle regulations came into effect could also be factors in observed differences in shark catch rates.

4.8. Proportion of Caught Turtles Alive vs. Dead

The Hawaii-based longline swordfish fishery is a relatively shallow-set fishery with light gear, such that caught turtles are able to reach the surface to breath during the gear soak.

Deeper-setting longline fisheries, which tend to use heavier gear, have relatively higher rates of caught sea turtles drowned when brought to the vessel during line hauling (Gilman et al., 2006a).

4.9. Proportion of Hooked Turtles with vs. without Terminal Tackle Attached Upon Release

The observed difference between the two time periods is likely primarily a result of the sea turtle regulations requiring Hawaii longline vessels to carry and use turtle release equipment (dip net, dehookers, etc.) while no such requirement was in place prior to the regulations. Also, a smaller proportion of hooked turtles being deeply hooked in the second period, likely a result of switching from a J to circle hook, might have made it easier to remove hooks than when a higher proportion of turtles were deeply hooked. Hawaii longline fishers believe that circle hooks are more difficult to remove (from a turtle, fish, or person) than J and Japan tuna style hooks. Turtles released with a hook and line attached may have lower post release survival prospects relative to hooked turtles that have had gear removed before being released.

4.10. Length of Caught Turtles

Average length of caught loggerhead turtles was greater during the period after the sea turtle regulations came into effect than during the period before the regulations when comparing the straight carapace and curved carapace lengths of loggerheads that were (i) mouth hooked and ingested hooks, (ii) foul-hooked in the body or entangled, or (iii) all caught loggerheads, however differences in length were not significantly different. When comparing the length of caught loggerhead turtles for just the first quarters of the periods before vs. after the turtle regulations came into effect, again the average length of caught loggerheads for the same three categories was greater during the period after the regulations came into effect, but the differences were not significant. Results eliminate any possible seasonal effect that might have occurred during this first quarter. For loggerheads that were hooked in the mouth or ingested the hook, the larger size of turtles caught after the turtle regulations came into effect is likely a result of only larger turtles being capable of fitting the wider 18/0 circle hook in their mouths relative to the narrower 9/0 hooks used before the regulations came into effect. However, it is unclear why larger turtles were caught by entanglement or foul-hooked in the body for the period after the regulations came into effect.

4.11. 2005 vs. 2006 Turtle Capture Rates and Annual Turtle Interaction Caps

The higher fishing effort during the first quarter of 2006 relative to 2005 is the cause of the higher number of loggerhead captures and not from a significant change in turtle capture rate.

4.12. Spatial and Temporal Closures

Area and seasonal fishery closures are one approach for pelagic longline fisheries to avoid peak areas and periods of sea turtle foraging, nesting, and migration (Kleiber and Boggs 2000). Based on the comparison of swordfish and turtle CPUE by quarter, the voluntary historical practice of concentrating 34% of swordfish fishing effort in the second quarter of the year when sea turtle CPUE is lowest has resulted in lower turtle captures than if effort were distributed more evenly by quarter. There is no obvious change to temporal distribution of effort to reduce turtle catch rates that would not have an adverse affect on fishing efficiency: if the fishery was required to reduce effort in the first quarter and increase effort in the second quarter (when the turtle catch rate is significantly lowest), this would result in a significant reduction in the swordfish catch rate. Additional research could be conducted to determine how to time the opening of the Hawaii-based longline swordfish fishery to optimize profitability.

This assessment should consider factors such as distance to fishing grounds at different seasons, and concomitant temporal differences in fuel costs, as well as the seasonal affect of weather conditions on fishing efficiency.

There were two areas with relatively high turtle capture rates that had a relatively small proportion of the fleets' fishing effort, indicating that closing areas at a 5 degree cell-scale incorporating these areas would have reduced turtle capture rates without eliminating main fishing areas. However, closing these high turtle catch rate areas to Hawaii-based longline swordfish vessels at a scale of 5 degree cells might result in displacing effort to other areas where the turtle capture rate might not be significantly different, thus not reducing total turtle captures. Additional research might result in identifying a temporal area closure that could result in substantial avoidance of turtle captures without compromising annual profitability.

Establishing protected areas containing turtle nesting colonies and adjacent waters is potentially an expedient method to reduce interactions between sea turtles and commercial fisheries. However, establishing high seas marine protected areas to restrict fishing in sea turtle foraging areas and migration routes, which would require extensive and dynamic boundaries defined in part by the location of large-scale oceanographic features and short-lived hydrographic features such as eddies and fronts, and would require extensive buffers, may not be a viable short-term solution. This is due in part to the extensive time anticipated to resolve legal complications with international treaties, to achieve international consensus and political will, and to acquire requisite extensive resources for enforcement (Thiel and Gilman 2001).

Before instituting a seasonal or spatial closure designed to reduce turtle interactions, analysis of the potential effects on bycatch rates of other sensitive species groups, such as seabirds, sharks, and cetaceans, should be conducted.

Marine protected areas have potential limitations, which can be avoided and minimized through careful planning and management (Gilman, 2002). For instance, resource use restrictions of a marine protected area may displace effort to adjacent and potentially more sensitive areas, especially if an effective management regime does not exist for these other areas. For example, closure of the Northwest Atlantic to the U.S. pelagic longline swordfish fleet may have had negative consequences for some sea turtle populations by displacing longline effort to alternative grounds such as the South Atlantic (Kotas *et al.* 2004). And instituting a closure for one longline fleet may result in an increase in effort by another nation's longline fleet with fewer controls to manage bycatch. For example, during the four-year closure of the Hawaii longline swordfish fishery, swordfish supply to the U.S. market traditionally met by the Hawaii fleet was replaced by imports from foreign longline fleets, including from Mexico, Panama, Costa Rica, and South Africa, which lack measures to manage turtle interactions, have substantially higher ratios of sea turtle captures to unit weight of swordfish catch, and likely have higher seabird bycatch rates than the Hawaii-based longline fleet (Bartram and Kaneko 2004; Sarmiento 2004).

Research through additional analysis of the Hawaii longline observer database may identify a moon phase during which sea turtle capture rates are relatively high but catch rates of marketable species are not relatively high. If this is the case, then the institution of a voluntary or formal constraint on fishing during this moon phase could be an effective and economically viable method to reduce sea turtle captures. If there is a higher loggerhead capture rate during one moon phase, the cause of this higher turtle catch rate can be explored (e.g., are vessels using different fishing methods or gear during this moon phase), and the effect on turtle and target species CPUE from a temporal closure to avoid these periods of high monthly turtle catch rates can be explored.

4.13. Turtle and Fish CPUE by Hook Position

The observer data indicate the number of hooks in a basket for an entire set. However, the number of hooks per basket may not be identical for all of the baskets in a set, thus introducing a potential source of error for these analyses. For instance, a turtle caught on hook number 4 in a set that is recorded as having 4 hooks in a basket may have been caught in a basket that actually contained more than 4 hooks, or conversely, a turtle recorded as being caught on hook number 3 in a set recorded as having 4 hooks in a basket may have been caught in a basket actually containing only 3 hooks.

Hooks next to floats are likely shallower than hooks not immediately next to floats, and the differential in depth likely increases the more hooks that are included in a basket. Sea turtles spend a majority of their time at depths < 40 m (Swimmer *et al*. 2002; Polovina *et al*. 2003,2004; Watson *et al*. 2003), indicating that setting longline gear deeper than 40 m will reduce turtle captures. The depths of the hooks will vary by vessel as well as by basket for an individual vessel due to variability in gear and fishing methods, such as differences in float line and branch line lengths, distance between floats, how taught the main line is when set, and the use, amount, and placement of weighted swivels on branch lines, to name a few of the variables that affect the depth of baited hooks. It is also possible that turtles are attracted to floats and follow float lines down to baited hooks, or that the jigging effect buoy action makes baited hooks closest to float lines relatively more attractive to turtles. Both of these possible mechanisms would result in higher turtle catch rates on hooks closest to float lines.

Empirical evidence directly demonstrating the turtle avoidance effectiveness of modifying longline gear configuration to set gear deeper is currently lacking. This is a research priority (Gilman et al., 2006a). The experimental treatment in Watson et al. (2002) could not achieve the depths that might have reduced turtle capture, however, movement of branchlines further from float lines enabled an assessment of this effect on turtle capture rates. Other studies of deeper gear alternatives were not designed to test effectiveness at reducing turtle interactions (Boggs 2003 and 2004; Beverly and Robinson 2004; Shiode *et al*, In Press). Instead, these were preliminary short-term trials of commercial viability and gear design feasibility.

The observation that there was no significant difference between catch rates of sea turtles on hooks in a basket that are not located next to floats vs. hooks located immediately next to floats likely indicates that the depth of baited hooks in these two groups are not substantially different, and that all of the hooks are at depths where sea turtles are abundant. This indicates that baited hooks would need to be set at depths deeper than the current deepest hook in a basket to result in substantial benefits towards reducing turtle catch rates. The observation that there was significantly higher swordfish CPUE on hooks in a basket not located immediately next to float lines indicates that setting baited hooks at the depths of the current deepest hook and possibly deeper may enable the fleet to increase target species CPUE.

5. CONCLUSIONS AND RECOMMENDATIONS

Results from this study are generally consistent with findings from studies in other pelagic longline fisheries that determined that switching to a wider circle hook from a narrower J or Japan tuna hook and switching from squid to fish for bait reduces turtle capture rates and reduces the proportion of caught turtles that are deeply hooked (Gilman et al., 2006a). The observation of reduced shark capture rate supports results from other studies that using fish instead of squid for bait will significantly reduce shark capture (Watson et al., 2005). Results identify effective and commercially viable turtle avoidance methods that can be exported to other longline fisheries worldwide, potentially resulting in substantial reductions in turtle bycatch in global pelagic longline fisheries.

It will become increasingly important for onboard observers to record specifics of fishing gear and methods employed by longline vessels to enable assessments of various factors on turtle capture rates. For instance, the Hawaii-based longline swordfish fleet is expected to begin to use two types of circle hooks with the opening of the season in 2007. A new 18/0 circle hook with a ring is now commercially available, and it is possible that the inclusion of the ring could result in different sea turtle catch rates than the older style of hook, which lacks the ring. Thus, it will be important for observers to record which style of hook vessels are using and on which type of hook on which turtles are caught.

Additional research through analysis of the Hawaii-based longline observer program database and at-sea experiments and commercial demonstrations will contribute to identifying causes of and solutions to high turtle capture rates. Interactions with sea turtles, seabirds, cetaceans, and sharks in pelagic longline fisheries are priority management concerns (Hall et al., 2000; FAO, 1999a,b, 2004a,b; Gilman et al., 2005, 2006a, 2006b, In Press a,b). It would be important to identify any conflicts as well as mutual benefits of bycatch and depredation reduction strategies among species groups when making conclusions and recommendations from this proposed study. For instance, line sink weight effects on seabird interactions should be considered when evaluating weighting design effects on turtle interactions, while changes in bait may affect interactions with all four species groups.

5.1. Differences between Vessels with High vs. Low Sea Turtle Capture Rates

It is a research priority to investigate the differences between Hawaii-based longline swordfish vessels with high vs. low turtle capture rates. Effects of the following design and operational differences on turtle catch rates to be investigated include but are not limited to:

- Lengths of float and branch lines (the expectation is that vessels setting gear shallower will have a higher turtle catch rate);
- Amount and placement of weight on branch lines (weight placed close to hooks and higher amount of weight may result in deeper setting of baited hooks, and reduced turtle interactions);
- Number of hooks in a basket and therefore the total number of buoys deployed and depth of baited hooks (in particular, assess if there is a correlation between increased number of floats and increased incidence of turtle entanglements, and if there is a negative correlation between the number of hooks in a basket, which is an index for the depth of baited hooks, and the rate of hooking turtles);
- Float line material - tarred line vs. monofilament line (are turtle entanglement rates lower for vessels using tarred line because the line is relatively more visible, does the increased visibility of tarred line result in increased turtle attraction to the gear and hence a higher turtle catch rate, or does tarred line increase entanglements because it knots and loops more easily than monofilament line?);
- Timing of setting and hauling (for the period before the turtle regulations came into effect). Research shows that loggerhead capture rates increase with increased length of daytime line retrieval (Bolten and Bjorndal, 2003), while research with hook timers indicates that leatherbacks are hooked more frequently at night (Watson *et al*. 2004);
- Proportion of branch lines containing light sticks and types of light sticks used;
- Vessel remote sensing capabilities; and
- Different types of main line floats.

Statistical analysis could also be conducted to determine if combinations of fishing gear and methods correlate with high vs. low turtle catch rates. For instance, vessels that set their gear during the daytime plus have little or no weight on branch lines might have relatively high turtle catch rates because their gear sink rate is slow as the gear moves through shallow waters where turtle foraging activity is highest, providing more time for turtles to encounter baited hooks during the day when the gear is more visible than at night.

Also, part of this study would be to assess differences in temporal and spatial distribution of effort by vessels with high vs. low turtle catch rates. We now know that there are significantly different turtle catch rates for different seasons. Therefore, for example, if a vessel is observed to have a relatively low turtle catch rate, if observer data show that this vessel conducts a high proportion of its fishing effort during seasons with the lowest turtle catch rates, this will help explain the observed low turtle catch rate for that vessel.

This study should also assess if the vessels with higher turtle CPUE also have higher catch rates of marketable fish species, especially for the period after the turtle regulations came into effect, which has created an incentive for vessels to fish at times and locations where turtle abundance is high if target fish species CPUE is high.

5.2. Deeper Setting

Another research priority is to assess the efficacy at reducing turtle catch rate and commercial viability of setting Hawaii-based longline swordfish gear deeper, below depths where sea turtles are believed to be most abundant (Beverly and Robinson 2004; Gilman et al., 2006a; Shiode *et al*, In Press). If deeper setting is demonstrated to be economically viable, regulations could establish specifications for main line shooter and vessel setting speed, float and branch line lengths, and amount and location of weights.

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