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# Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery

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ABSTRACT

The reduction of sea turtle mortality in fisheries may contribute to recovering populations. To reduce turtle interactions, regulations for the Hawaii-based longline swordfish fishery required vessels to switch from using a J-shaped hook with squid bait to a wider circle-shaped hook with fish bait. Analyses of observer data showed that, following the introduction of the regulations, significant and large reductions in sea turtle and shark capture rates occurred without compromising target species catches. Capture rates of leatherback and loggerhead turtles significantly declined by 83% and 90%, respectively. The swordfish catch rate significantly increased by 16%. However, combined tuna species and combined mahimahi, opah, and wahoo catch rates significantly declined by 50% and 34%, respectively. The shark catch rate significantly declined by 36%, highlighting the potential for the use of fish instead of squid for bait to contribute to addressing concerns over the sustainability of current levels of shark exploitation. There was also a highly significant reduction in the proportion of turtles that swallowed hooks (versus being hooked in the mouth or body or entangled) and a highly significant increase in the proportion of caught turtles that were released after removal of all terminal tackle, which may increase the likelihood of turtles surviving the interaction. A quarter of turtle captures were in clusters (>1 turtle caught per set and consecutive sets with turtle captures), which is substantially higher than predicted by chance if the events were independent. This suggests that turtles aggregate at foraging grounds and that instituting methods to avoid real-time turtle bycatch hotspots may further reduce turtle interactions. There was no significant correlation between turtle and swordfish catch rates (vessels with high swordfish CPUE do not necessarily have high turtle CPUE), indicating that there may be a fishing practice or gear design causing some vessels to have low turtle catch rates without compromising swordfish catch rates.



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## 1. Introduction

Reducing sea turtle bycatch in pelagic longline fisheries, in concert with activities to reduce other anthropogenic mortality sources, may halt and reverse population declines (Spotila et al., 1996, 2000; Hatase et al., 2002; Kamezaki et al., 2003; Limpus and Limpus, 2003; FAO, 2004a,b). Due to concerns over interactions with turtles, the Hawaii-based longline swordfish (*Xiphias gladius*) fishery was closed for over two years and is now subject to strict management measures. These measures include prescribed use of 10° 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 (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtle captures, and 100% onboard observer coverage (US National Marine Fisheries Service, 2004a).

Assessment of turtle avoidance measures in the Hawaii longline swordfish fishery contributes to a small but growing body of research. Research on methods to avoid sea turtles in pelagic longline fisheries has been initiated only recently. Most experiments had small sample sizes and had been conducted over only a few seasons in a small number of fisheries (Gilman et al., 2006a). The potential for avoiding real-time sea turtle bycatch hotspots has been identified (Gilman et al., 2006b), but currently there is a lack of empirical evidence demonstrating that fishing in an identified turtle hotspot increases a vessel's probability of catching a turtle. Furthermore, few studies considered effects of turtle avoidance methods on other bycatch species, including seabirds (Gilman et al., 2005), sharks (Gilman et al., 2007) and cetaceans (Gilman et al., 2006c). For instance, there is growing understanding of the significant effect hook and bait types have on shark catch rates (Bolten and Bjorndal, 2002, 2003; Watson et al., 2005; Yokota et al., 2006). This is of interest due to concerns over the status of some shark populations, the sustainability of their exploitation and ecosystem-level effects from shark population declines (FAO, 1999; Bonfil, 2002; Baum and Myers, 2004; Baum et al., 2003; Burgess et al., 2005a,b; Fowler et al., 2005; Ward and Meyers, 2005). Despite limited but growing evidence of the turtle avoidance efficacy and economic viability of circle hooks and fish bait in some fisheries (Bolten and Bjorndal, 2005; Largacha et al., 2005; Watson et al., 2005), it is important to test these turtle avoidance methods in individual fleets such as implemented in the Hawaii fleet. This is because the effectiveness and commercial viability of a turtle avoidance strategy, including changes in hook and bait, may be fishery-specific, depending on the size and species of turtles and target fish and other differences among fleets (FAO, 2004a,b; Gilman et al., 2006a).

Fishery management authorities based the Hawaii regulations on results from experiments by Watson et al. (2005) in the US North Atlantic longline swordfish fishery. Watson et al. (2005) found that use of 18/0 circle hooks with fish bait significantly reduced sea turtle bycatch rates compared to narrower 9/0 J hooks with squid bait. The proportion of caught turtles that swallowed hooks into the esophagus or deeper (deep hooking) was also reduced without compromising catch rates of some target species (Watson et al., 2005).

Two additional experiments also demonstrated the efficacy at reducing turtle interactions and economic viability of switching from J and Japan tuna hooks to wider circle hooks and switching from squid to fish for bait (Bolten and Bjorndal, 2005; Largacha et al., 2005; Gilman et al., 2006a; Read, 2007). In the Azores longline swordfish and blue shark (*Prionace glauca*) fishery, non-offset 16/0 and 18/0 circle hooks resulted in significantly lower loggerhead turtle catch rates compared to a Japan tuna 3.6 hook. Furthermore, the proportion of deeply hooked loggerheads was significantly lower when fishing with circle hooks compared to non-offset 9/0 J hooks (Bolten and Bjorndal, 2005). The effect of the circle hooks on target and incidental species catch per unit of effort (CPUE) is unclear in the Azores study as blue sharks were not targeted during part of the study period and the authors did not clearly present results for swordfish CPUE and did not present results for incidental species CPUE (Bolten and Bjorndal, 2005). Furthermore this in the Ecuador longline tuna fishery, 10° offset 18/0 circle hooks significantly reduced turtle CPUE compared to J and Japan tuna hooks, with a small and non-significant 9.5% reduction in tuna CPUE (Largacha et al., 2005). Additional research conducted in the Hawaii longline fleet on methods to reduce sea turtle interactions using circle hooks (LaGrange, 2001; Boggs, 2003, 2004), as well as using deeper-setting (Boggs, 2003, 2004) and camouflaged gear (Boggs, 2003, 2004) did not identify effective or commercially viable turtle avoidance methods. However, these experiments were small and the deep-setting experiment was not implemented according to design (Gilman et al., 2006a).

Loggerhead and other hard-shelled turtles tend to get caught in longline gear by biting a baited hook while leatherbacks tend to get caught by becoming foul-hooked on the body and entangled in line (Bolten and Bjorndal, 2002, 2003; Javitech Limited, 2002, 2003; Watson et al., 2003). Therefore, the effectiveness of circle hooks at reducing captures of hard-shelled turtles as demonstrated by Bolten and Bjorndal (2005), Largacha et al. (2005) and Watson et al. (2005), may be due to their being wider at the narrowest point compared to control treatment hooks. The circle hooks may have been too wide for the hard-shelled turtles to fit in their mouths. 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). The point on circle hooks is turned in toward the hook shank and the gap between a 4.9 cm-wide 10° offset 18/0 circle hook's point and shaft is smaller than a 4.0 cm-wide 9/0 J hook (Fig. 1). Differences in hook designs other than narrowest width and orientation of point (i.e. length, gape, bite) as well as materials may also be important variables affecting sea turtle capture rates and location of hooking.

Turtles are believed to feed differently on squid vs. fish. Observations of foraging captive turtles revealed that they tended to progressively eat fish bait in small bites until they completely removed the fish from the hook. When turtles bit a hook containing fish bait, they carefully removed the remaining fish bait from the hook and avoided ingesting the hook. However, turtles tended to line squid up with their flippers and gulp it down whole, ingesting the hook and bait together, perhaps because they had difficulty biting off pieces of the squid due to its rubbery and firm flesh relative to fish (Watson et al., 2003, 2004).

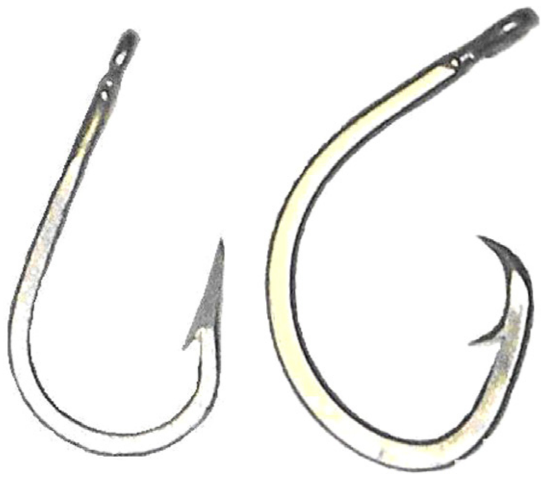

**Fig. 1 – Mustad 9/0 J hook (left) and Lingren-Pitman 10° offset 18/0 circle hook (photo E. Gilman).**

We analyzed data from the US National Marine Fisheries Service observer program for the Hawaii-based pelagic longline swordfish fishery to infer the effects of the sea turtle regulations on (i) turtle catch rates; (ii) changes in interactions with turtle (proportion of turtles that are lightly hooked vs. deeply hooked vs. entangled, and proportion of caught turtles that are released with vs. without terminal tackle attached) to assess possible effects on the likelihood of turtles surviving the longline interaction; (iii) change in the proportion of turtles that were alive vs. dead when hauled to the vessel; (iv) catch rate of retained fish; and (v) catch rate of sharks. We also investigated (vi) the rarity of turtle interactions and the frequency of turtles being caught in clusters. Finally, (vii) we compared the total number of turtles caught by individual vessels, compared turtle and swordfish CPUE of individual vessels and determined if turtle and swordfish CPUE were correlated.

## 2. Methods

We analyzed data from the Hawaii longline observer program for Hawaii-based longline swordfish-targeting sets for the periods before and after regulations designed to reduce turtle interactions came into effect. Parameters were compared for (i) the period prior to the sea turtle regulations, from 2 March 1994 to 20 February 2002, and (ii) the period after regulations were introduced, from 3 May 2004 to 19 March 2006. Swordfish sets did not occur between 21 February 2002 and 3 May 2004 during a temporary closure of this component of the Hawaii-based longline fleet. The last swordfish set in 2006 was on 19 March when the swordfish fishery was closed for the year when an annual cap of 17 loggerhead turtle captures was reached. Before the regulations, there were 120 observed Hawaii-based pelagic longline swordfish trips during which 1631 sets of 1,282,748 hooks were made. After the regulations came into effect, there were 164 observed trips during which 2631 sets of 2,150,674 hooks were made.

For the assessment of the proportion of caught turtles that were lightly hooked (hooked in the mouth or body), deeply hooked (hooks are swallowed into the esophagus or deeper) and entangled, if a turtle was observed to be both hooked and entangled, we counted it as being hooked only. Several analyses were conducted by quarter (e.g., 'first quarter' signifies January–March) in addition to the full period to assess possible effects of seasonality and temporal distribution of fishing effort. Turtle captures were defined as occurring in 'clusters' for sets where >1 turtle was caught and for consecutive sets with ⩾1 turtle caught.

Probable error of point estimates are reported as non-parametric 95% confidence intervals derived from percentile method bootstrapping at $N = 1000$ (Efron and Tibshirani, 1986). The probability of the observed occurrence of clustered turtle capture events was determined using a random number generator simulated 15,000 times. The chi-square test was used to determine any 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 (hook, line, and if used, wire leader and weighted swivel) attached.

## 3. Results

### 3.1. Turtle captures

The combined turtle species catch rate significantly declined by 89.1% from the period before to after the turtle regulations came into effect (Fig. 2). Loggerhead and leatherback capture rates significantly declined by 90.0% and 82.8%, respectively (Fig. 2). Sea turtle catch rates were also significantly lower for combined and individual turtle species by quarter for the two study periods, except the leatherback turtle catch rate during the first quarters of the two study periods was not significantly different.

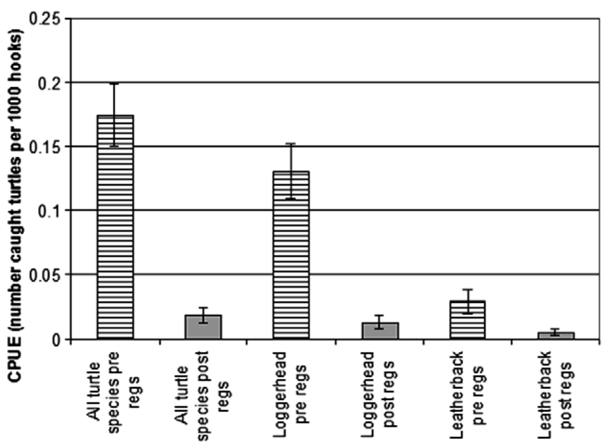


**Fig. 2 – Sea turtle capture rates (captures per 1000 hooks) in the Hawaii-based pelagic longline swordfish fishery for combined turtle species, loggerhead turtles, and leatherback turtles, for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are bootstrapped (N = 1000) 95% non-parametric confidence intervals.**

Since observer coverage for this fishery began, of the 231 sets where one or more turtle was caught, 24% (55) were in consecutive sets (two or more sets in a row). There is less than a 0.4% ($P < 0.005$) probability that ⩾24% of the 231 sets with caught turtles would be consecutive if the events were independent and not serially correlated. Turtles were caught on 0.008% of observed hooks. One or more turtle was caught in 5.4% of the observed 4262 sets. Of the 264 caught turtles, 77% (202) were caught alone (one turtle caught in a single set) with the remaining 23% (62) being caught in a set with two or more turtle captures.

Since observer coverage for this fishery began, 68 vessels made swordfish sets, of which 53 caught ⩾one turtle. Half of the fleet caught <three turtles. The maximum number of turtles caught by a single vessel was 23 (Fig. 3). This vessel had a sea turtle capture rate 3.8 times higher than the fishery average.

### 3.2. *Retained fish catch rates*

Fig. 4 shows the CPUE of retained fish for the periods before and after the sea turtle regulations came into effect. Swordfish CPUE significantly increased by 16.0% while combined tuna species CPUE and combined mahimahi, opah, and wahoo CPUE was significantly lower by 50.0% and 34.1%, respectively, in the period after the regulations. The CPUE of combined species of retained fish for the two periods was not significantly different, dropping by 2.6% from the first to second period.

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 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. Differences were significant for the first, second, and fourth quarters, but not for the third quarter.

### 3.3. *Correlation between retained swordfish and turtle catch rates*

Fig. 5 shows the retained swordfish and turtle (combined species) catch rates for the 68 vessels that have made ⩾one set targeting swordfish. 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 0.094 turtles per 1000 hooks (±0.01 SD of the mean, $N = 68$, range 0–0.4). The mean retained swordfish CPUE was 14.74 swordfish per 1000 hooks (±0.70 SD of the mean, $N = 68$, range 0–26.8). Of these 68 vessels, 53 caught ⩾one turtle during the observed period while 15 vessels did not catch a turtle. The two vessels that caught zero swordfish each made only a single fishing trip to target swordfish.

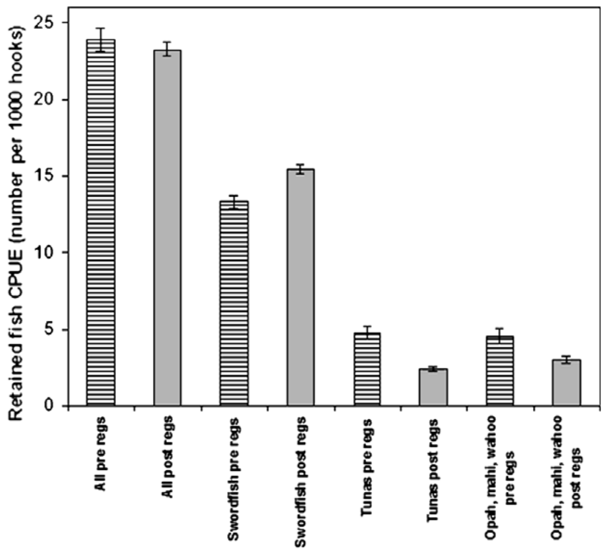


**Fig. 4 – Retained fish combined species CPUE (number per 1000 hooks) in the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are bootstrapped (N = 1000) 95% non-parametric confidence intervals.**

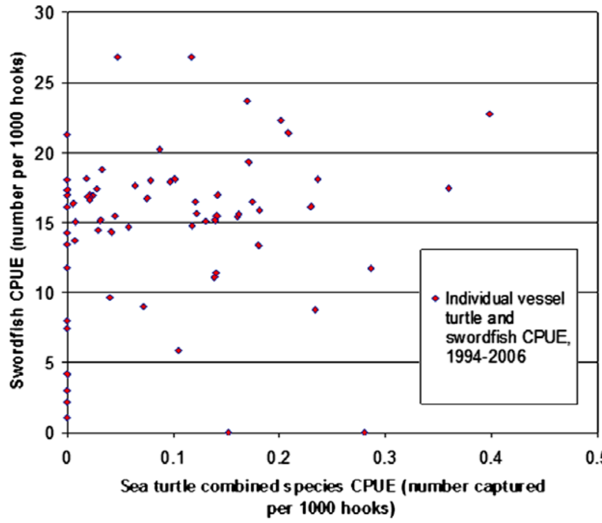


**Fig. 5 – Catch rate of retained swordfish and sea turtles combined species of individual vessels of the Hawaii-based longline swordfish fishery, 1994–2006 (N = 68).**

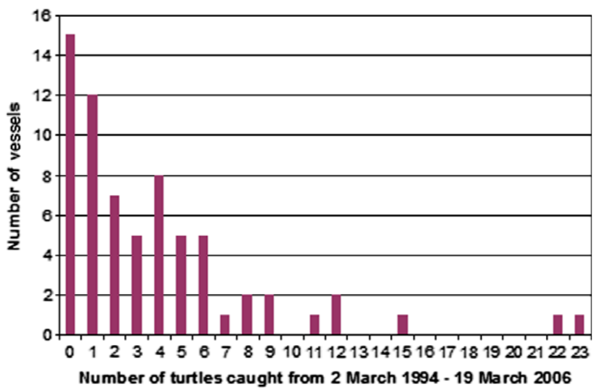


**Fig. 3 – Number of Hawaii-based longline swordfish vessels that caught from 0 to 23 turtles, 1994–2006.**

### 3.4. Shark catch rates

Fig. 6 shows shark CPUE by quarter and full periods before and after the sea turtle regulations came into effect. The post-regulations combined species shark catch rate (14.0 sharks per 1000 hooks, 13.6–14.5 95% CI) significantly declined by 36% from the pre-regulations shark catch rate (21.9 sharks per 1000 hooks, 20.4–23.5 95% CI). Shark CPUE was also significantly lower in the period after the regulations came into effect by quarter of each of the two study periods (Fig. 6).

### 3.5. Proportion of caught turtles alive vs. dead, and lightly hooked vs. deeply hooked vs. entangled

Prior to the sea turtle regulations, of the 182 caught hard-shelled turtles of known condition, 99% were alive, while 100% of 35 caught leatherbacks of known condition were alive. One hundred percent of 27 hard-shelled turtles and 11 leatherbacks of known condition caught after turtle regulations came into effect were alive. There was no significant difference in the proportion of alive vs. dead turtles for combined species observed captured between the two study periods (Chi-square test, $\chi^2 = 0.483$, DF = 1, $P > 0.05$).

There was a highly significant difference in the proportion of deeply hooked turtles for combined species observed captured between the two study periods (Chi-square test, $\chi^2 = 16.728$, DF = 1, $P < 0.01$). For the period before the regulations, 38% of caught hard-shelled turtles were lightly hooked, 60% were deeply hooked and 2% were entangled ($N = 180$, 163 loggerhead turtles). After the regulations, 63% of caught hard-shelled turtles were lightly hooked, 22% were deeply hooked and 15% were entangled ($N = 27$, all loggerheads). Before the turtle regulations came into effect, 6% of leatherbacks were entangled, 84% were lightly hooked and 10% were deeply hooked ($N = 31$). After the turtle regulations, 100% were lightly hooked ($N = 10$).

### 3.6. Proportion of hooked turtles released with vs. without gear removed

Before the sea turtle regulations came into effect, 40% of hooked turtles were released after removing all terminal tackle ($N = 178$). After the sea turtle regulations came into effect, 67% of hooked turtles were released after the removal of all terminal tackle ($N = 33$). There was a highly 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 (Chi-square test $\chi^2 = 7.746$, DF = 1, $P < 0.01$).

## 4. Discussion

### 4.1. Turtle catch rates

Sea turtle capture rates were an order of magnitude lower following the introduction of the sea turtle regulations. This is consistent with results from controlled and comparative experiments on the effects of switching from a J or Japan hook to a wider circle hook and switching from squid to fish for bait (Bolten and Bjorndal, 2005; Watson et al., 2005; Largacha et al., 2005; Gilman et al., 2006a; Read, 2007). Turtle catch rates were also significantly lower for combined turtle species and individual species by quarter for the two study periods, except for the leatherback turtle catch rate during the first quarter of the two study periods. Thus, a difference in temporal distribution of fishing effort between the two periods is not likely a large factor in explaining observed differences in turtle CPUE.

### 4.2. Proportion of caught turtles lightly hooked vs. deeply hooked vs. entangled

Controlled and comparative experiments have documented reductions in the proportion of deeply hooked turtles when switching from a J or Japan tuna hook to a wider circle hook (Bolten and Bjorndal, 2005; Watson et al., 2005; Largacha et al., 2005; Gilman et al., 2006a; Read, 2007). Results

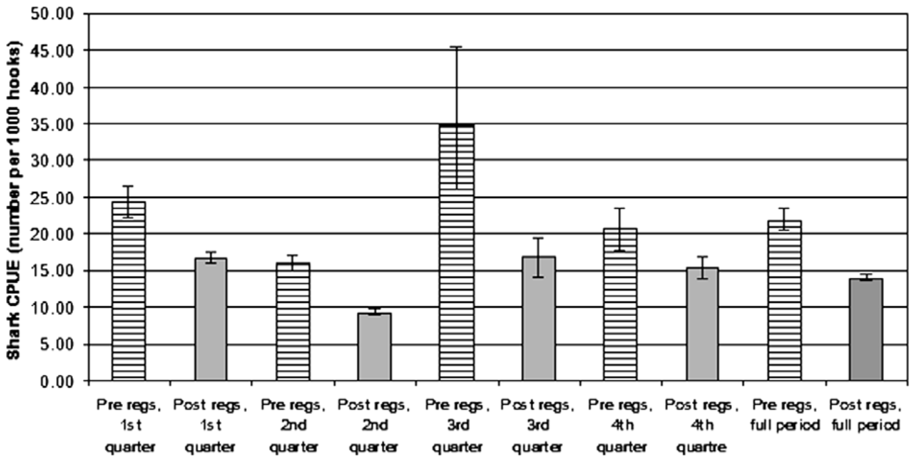


**Fig. 6 – Shark combined species CPUE (number per 1000 hooks) in the Hawaii-based longline swordfish fishery for the periods before and after regulations designed to reduce sea turtle captures came into effect. Error bars are bootstrapped (N = 1000) 95% non-parametric confidence intervals.**

presented here were consistent with these studies. The reduction in the proportion of hooked hard-shelled turtles and increase in the proportion that were entangled suggests that turtles caught in the Hawaii swordfish fishery are experiencing less severe injuries as a result of interactions with longline gear, assuming that entangled turtles are released in better condition than hooked turtles. Also, US fishery management authorities hypothesize that mouth-hooked turtles have higher post-hooking survival rates than more deeply hooked turtles (Epperly and Boggs, 2004). The US fishery management authority's current practice for estimating turtle mortality in longline fisheries considers whether or not gear is removed from a turtle prior to release (US National Marine Fisheries Service, 2004b). Gear removal is more readily accomplished with lightly hooked versus more deeply hooked turtles. Post-release-mortality of loggerhead and leatherback turtles interacting with US North Atlantic pelagic longline swordfish gear using J hooks is estimated to be 40% and 32%, respectively, which assumes that fishers remove gear from and release light-hooked turtles and that deeper hooking causes greater mortality (US National Marine Fisheries Service, 2004b).

### 4.3. *Correlation between swordfish and turtle catch rates*

The observation of large variability in turtle and target species catch rates among individual vessels (Fig. 5) and a lack of a significant correlation between turtle and swordfish catch rates indicates that vessels with high swordfish catch rates do not necessarily have high turtle catch rates. This suggests that there may be fishing methods or gear designs that allow some vessels to have low turtle catch rates and high swordfish catch rates. The maximum number of turtles caught by a single vessel was 23. This vessel had a sea turtle capture rate 3.8 times the average of the swordfish fleet, while its swordfish catch rate was slightly below the fleet's mean. This one vessel, representing 1.5% of the number of vessels participating in the fishery, caught 9% of the turtles. Another vessel had a swordfish catch rate 1.8 times higher than the fleet's average and a turtle catch rate that was half the fleet's average. It is a research priority to investigate differences among Hawaii-based longline swordfish vessels with (i) high turtle capture rates and low swordfish catch rates and (ii) low turtle and high swordfish catch rates. Results may enable identification of further strategies to reduce turtle catch rates without compromising economic viability.

### 4.4. *Rarity of turtle captures*

From a localised perspective, turtle captures are an extremely rare event. However, cumulatively, fleet and region-wide, mortality from longline interactions may contribute to population-level effects and represent a substantial threat faced by this sensitive species group. In light of the dire conservation status of many sea turtle populations, there is an interest in reducing all anthropogenic sources of sea turtle mortality to as close to zero as possible (Spotila et al., 1996, 2000; Hatase et al., 2002; Kamezaki et al., 2003; Limpus and Limpus, 2003; FAO, 2004a,b; Carranza et al., 2006).

A quarter of caught turtles were in 'clusters'. Given the rarity of turtle capture events, this is much higher than predicted to occur by chance if these events were independent. This suggests that sea turtles may aggregate at foraging grounds or other areas and that there may be a higher probability of catching a turtle in a set that follows a set where a turtle was caught. After a turtle is caught, moving vessel position a certain distance (e.g., >100 km) from this location or avoiding fishing in the vicinity for a certain time period (e.g., >one week) could reduce the probability of catching another turtle during the rest of the trip. Following a set with a turtle interaction, moving vessel position to different oceanographic conditions, such as moving away from an oceanic front or gyre (Polovina et al., 2000, 2004), or moving away from topographic features, such as a shelf break or seamount, may be effective methods to reduce the probability of turtle interactions in subsequent sets. Fleet communication programs can enable a vessel to share the position of a turtle interaction to the rest of the fleet to enable real-time fleet-wide avoidance of turtle bycatch hotspots (Gilman et al., 2006b).

### 4.5. *Retained fish catch rates*

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° offset 18/0 circle hook with fish bait was in use are consistent with results from a controlled experiment in the US North Atlantic longline swordfish fishery (Watson et al., 2005). More analysis could be conducted to assess the effects of the regulations on economic viability, such as by determining the change in ex-vessel value resulting from the observed changes in catch rates. Analysis could also determine if the required change in hook and bait is associated with a change in the quality of fish due to a change in the proportion of fish landed alive vs. dead.

### 4.6. *Shark catch rates*

The large and significant decrease in shark CPUE observed in this study is consistent with controlled and comparative studies, which found that switching from squid to fish for bait resulted in a large, significant reduction in shark CPUE, while switching from Japan tuna and J hooks to circle hooks caused no change or a significant but small increase in shark CPUE (Bolten and Bjorndal, 2002, 2003; Watson et al., 2005; Yokota et al., 2006). Research in the Azores longline swordfish and blue shark fishery, in a 2000 study where blue sharks were not being targeted, showed that non-offset 16/0 circle hooks produced a significantly higher blue shark CPUE than non-offset 9/0 J hooks (Bolten and Bjorndal, 2002). In a 2001 study in the Azores fishery, where 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 resulted in a significantly higher blue shark catch rate than fishing with a J hook. A study conducted in the US North Atlantic longline swordfish fishery found that use of a non-offset or 10° 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° offset 18/0 circle hook with mackerel bait and 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. Research in an experimental Japanese North Pacific longline fishery found no difference in the capture rate of blue sharks between a circle and Japan tuna hook (Yokota et al., 2006).

Thus, results from the Azores and US North Atlantic longline fisheries and the experimental Japanese North Pacific longline fishery indicate that it was likely the change in bait type that caused the decrease in shark CPUE in the Hawaii-based longline swordfish fishery. Pelagic sharks historically comprised about 50% of the total catch composition of the Hawaii-based longline swordfish fishery, and in most years blue sharks comprise more than 90% of total shark catch (Gilman et al., 2007). Almost all sharks are discarded alive in this fishery (in 2006, 93.4% of caught sharks were discarded alive, 6.1% were discarded dead, and 0.5% were retained), where rules prohibit retaining shark fins without also retaining the carcass (Gilman et al., 2007). However, in non-shark longline fisheries where a large proportion of caught sharks are killed (e.g., in the Peru and Chile artisanal pelagic longline mahi-mahi (*Coryphaena* spp) fisheries, almost all caught sharks are retained (Gilman et al., 2007)), these results indicate that use of fish instead of squid for bait will reduce shark fishing mortality.

### 4.7. *Proportion of caught turtles alive vs. dead*

The change in hook and bait did not cause a significantly different proportion of caught turtles to die during the gear soak. The Hawaii-based longline swordfish fishery is a relatively shallow-set fishery with light gear. As a result, caught turtles are able to reach the surface to breathe during the gear soak. Deeper-setting longline fisheries, which tend to use heavier gear, have a higher proportion of caught sea turtles drowned when hauled to the vessel (Gilman et al., 2006a).

### 4.8. *Proportion of released turtles with vs. without terminal tackle attached*

The observed difference in the proportion of turtles released with terminal tackle attached is likely primarily a result of the requirement for vessels to carry and use turtle release equipment (i.e. dip nets, dehookers, line clippers). The required change in hook and bait also may have contributed. Because a smaller proportion of hooked turtles were deeply hooked in the period when the turtle regulations were in effect, probably a result of switching from a J to circle-shaped hook, this may have made it easier for crew to remove hooks from caught turtles. While 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, it is easier to remove circle hooks from lightly hooked turtles than it is to remove J or Japan tuna hooks from deeply hooked turtles.

Turtles released with a hook and line attached may have a higher mortality rate than turtles released after gear removal (US National Marine Fisheries Service, 2004b). Therefore, since the introduction of the turtle regulations, a larger proportion of caught turtles may be surviving the longline interaction.

### 4.9. *Confounding factors*

The existence of confounding factors prevents drawing definitive conclusions regarding the single factor effects of hook and bait type on turtle and fish interactions for the periods before vs. after the Hawaii sea turtle regulations came into effect. However, the consistency in observations with results from relevant controlled and comparative experiments (Largacha et al., 2005; Bolten and Bjorndal, 2005; Watson et al., 2005; Gilman et al., 2006a) strongly supports the inference that the change in hook and bait were central factors in causing observed changes.

In addition to the change in hook and bait, other factors may have contributed to the observed changes in turtle and fish interactions. The Hawaii longline swordfish fishery has been required to employ methods to reduce seabird bycatch since 12 June 2001 (50 CFR 660.35, US National Marine Fisheries Service, 2002). These seabird avoidance regulations include requirements for swordfish-targeting vessels to night set and dye bait blue. These changes could have affected sea turtle and fish capture rates. After the night setting requirement came into effect, the mean time for initiating sets by swordfish vessels was 76 minutes later than before the night setting requirement. 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 prior to the sea turtle regulations. While research shows 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).

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 notices. This is a documented problem in some fisheries with measures to manage seabird bycatch (Gales et al., 1998; Gilman et al., 2005).

Another possible confounding factor is variability in turtle abundance at fishing grounds. 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 could have contributed to observed changes in turtle capture rates.

## 5. Management issues

Following a requirement to switch from J hooks with squid bait to wider circle hooks with fish bait, the Hawaii-based longline swordfish fishery has had significant and large reductions in sea turtle and shark capture rates without comprising target species catches. There was also a non-significant reduction in the proportion of deeply hooked turtles and a significant increase in the proportion of caught turtles that were released after removal of all terminal tackle, which may increase turtles' post-release survival prospects.

The effectiveness and commercial viability of a turtle avoidance strategy, including changes in hook and bait, may be fishery-specific. Results from this study are consistent with the three other experiments that provide evidence of the turtle avoidance efficacy and economic viability of circle hooks and fish bait (Bolten and Bjorndal, 2005; Largacha et al., 2005; Watson et al., 2005). This further supports having pelagic longline fisheries with sea turtle interactions that use J or Japan tuna hooks or squid bait assess the efficacy and economic viability of employing wider circle hooks and fish bait. If only a change to a circle hook is being considered, a possible increase in shark CPUE (Bolten and Bjorndal, 2002, 2003; Watson et al., 2005) should be taken into consideration.

Results further the understanding of the significant effect hook and bait types have on shark catch rates (Bolten and Bjorndal, 2002, 2003; Watson et al., 2005; Yokota et al., 2006). There has been recent international concern over the conservation status and sustainability of the exploitation of sharks in world fisheries (Baum and Myers, 2004; Baum et al., 2003; Fowler et al., 2005; Ward and Meyers, 2005). The use of fish instead of squid for bait in pelagic longline fisheries can reduce shark catch rates and reduce shark fishing mortality in some fisheries.

Results provide the first empirical evidence of a higher probability of catching a turtle in a set that follows a set where a turtle was caught. Thus suggests that practices by individual vessels and fleet coordination for real-time avoidance of areas with turtle captures holds promise. This is potentially another useful strategy for turtle avoidance for pelagic longline as well as other marine capture fisheries to reduce anthropogenic sources of sea turtle mortality to as close to zero as possible.

A few pelagic longline fisheries, including Hawaii, have adopted effective measures to manage turtle interactions (Largacha et al., 2005; Watson et al., 2005). To date, no Inter-Governmental Organizations, including Regional Fishery Management Organizations, have adopted legally binding measures for Members to employ sea turtle avoidance methods in marine capture fisheries (FAO, 2007). There is an urgent need for the uptake of fishery-specific turtle bycatch solutions by all relevant Regional Fishery Management Organizations and individual longline fleets with problematic sea turtle bycatch. However, this alone will be insufficient to recover turtle populations. There is a need to reduce anthropogenic sources of mortality other than longline fisheries bycatch, which include human hunting for adult turtles and eggs, destruction and disturbance of turtle nesting and foraging habitat, predation by introduced species, marine pollution and capture in other fishing gear (gillnet, purse seine, trawl) (Robins, 1995; Cheng and Chen, 1997; Bellagio Conference on Sea Turtles Steering Committee, 2004; FAO, 2004a,b; Koch et al., 2006). Reducing bycatch of sea turtles in pelagic longline fisheries, in parallel with activities to reduce these other anthropogenic mortality sources, may contribute to sea turtle recovery.

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