Fishing methods to reduce sea turtle mortality associated with pelagic longlines

John W. Watson, Sheryan P. Epperly, Arvind K. Shah, and Daniel G. Foster

Abstract: Changes in hook design and bait type were investigated as measures to reduce the bycatch of sea turtles on pelagic longlines in the western North Atlantic Ocean. Specifically, the effectiveness of 18/0 circle hooks and mackerel (*Scomber scombrus*) bait was evaluated with respect to reducing sea turtle interactions and maintaining swordfish (*Xiphias gladius*) and tuna (*Thunnus* spp.) catch rates. Individually, circle hooks and mackerel bait significantly reduced both loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtle bycatch. Circle hooks also significantly reduced the rate of hook ingestion by the loggerheads, potentially reducing postrelease mortality. The combination of circle hooks and mackerel bait was even more effective for loggerhead turtles and had no negative effect on swordfish catch. These modifications in fishing methods, in conjunction with tools developed to remove hooks and line from the turtles, significantly reduced the capture rate of sea turtles and potentially the post-hooking mortality of those that were caught and did not negatively impact the primary target species catch rate. In addition, these mitigation measures have the potential to reduce mortality of sea turtles and other bycatch species worldwide.

Résumé : Nous avons évalué les changements de forme des hameçons et de type d'appât sur les palangres pélagiques comme moyens de réduire les prises accessoires de tortues de mer dans la partie occidentale de l'Atlantique nord. Nous avons, en fait, évalué l'efficacité des hameçons autoferrants 18/0 et des appâts de maquereau (*Scomber scombrus*) pour restreindre les interactions avec les tortues de mer, tout en maintenant les taux de capture d'espadons (*Xiphias gladius*) et de thons (*Thunnus* spp.). Les hameçons autoferrants et les appâts de maquereau réduisent significativement, tous les deux, les prises accessoires des tortues de mer, tant des caouannes (*Caretta caretta*) que des tortues luth (*Dermochelys coriacea*). Les hameçons autoferrants réduisent aussi significativement le taux d'ingestion des hameçons chez les caouannes, ce qui diminue potentiellement la mortalité après la libération. L'utilisation combinée d'hameçons autoferrants et d'appâts de maquereau est encore plus efficace chez les caouannes, sans effet négatif sur la capture des espadons. Ces modifications des techniques de pêche et la mise au point d'outils pour retirer les hameçons et les lignes des tortues réduisent significativement le taux de capture des tortues de mer et diminuent potentiellement la mortalité d'après ferrage des tortues qui sont capturées, sans effet négatif sur le taux de capture des espèces principales ciblées. De plus, ces mesures de mitigation peuvent potentiellement réduire la mortalité des tortues de mer et des autres espèces dans les prises accessoires à l'échelle globale.

[Traduit par la Rédaction]

Introduction

Six of the seven extant species of sea turtles living in the world's oceans are listed as either critically endangered or endangered (IUCN 2003), and international trade of these species is prohibited (CITES 2003); the seventh species is listed as data deficient. They also are protected by the United States Endangered Species Act and similar laws of other nations. The failure worldwide of most sea turtle populations to recover is attributed, in part, to their incidental capture in fisheries (Hillestad et al. 1995; Lutcavage et al. 1996). Trawls (Magnuson et al. 1990; Poiner and Harris 1996), gill nets (De Metrio and Megalofonu 1988; Julian and Beeson 1998), and longlines (Camiñas 1997; Witzell 1999; Lewison et al. 2004) are gears known to interact with turtles worldwide. Bycatch (unintended and discarded catch) in trawls, identified as the most important source of human-associated mortality (Magnuson et al. 1990), is being addressed with turtle excluder devices (Epperly 2003). This paper focuses on pelagic longlines, which primarily target tuna (*Thunnus* spp.), swordfish (*Xiphias gladius*), and sharks (Squaliformes) worldwide, and on methods to significantly reduce the incidental bycatch of sea turtles in these fisheries.

Estimates of turtle takes in the Atlantic pelagic longline fisheries have raised concern that the pelagic longline fishery may be impacting the potential recovery of loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtle populations. From 1992 to 1999, the United States Atlantic pelagic longline fleet incidentally caught an estimated 7891 loggerhead and 6363 leatherback sea turtles (Yeung 2001); the United States fleet represents less than

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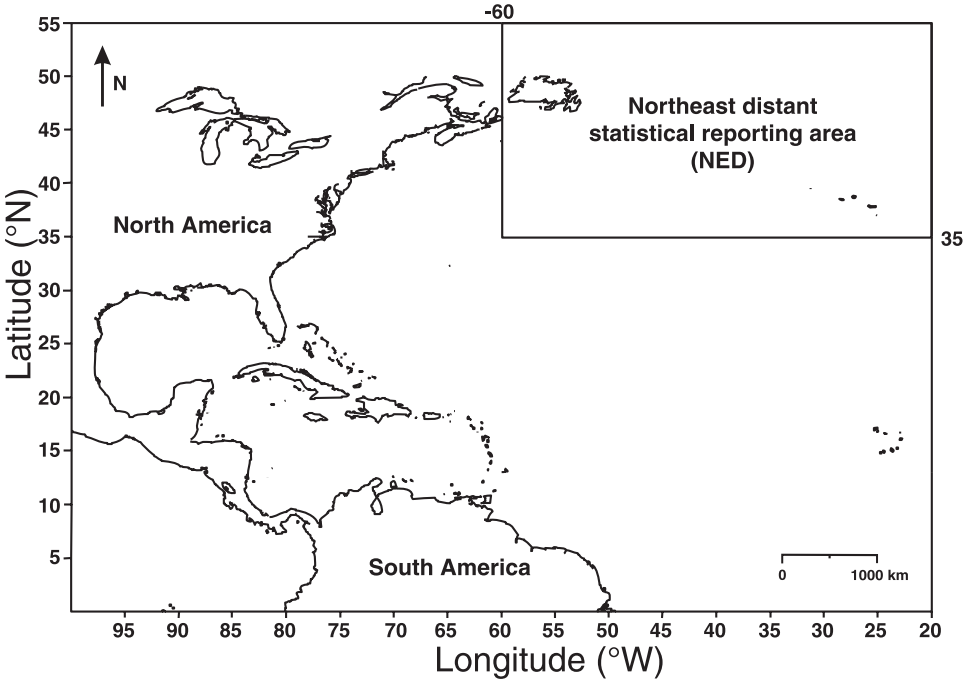
Fig. 1. The Northeast Distant Waters (NED) was closed to fishing 2001–2003 because of high sea turtle bycatch rates and was the study area for the bycatch experiments.



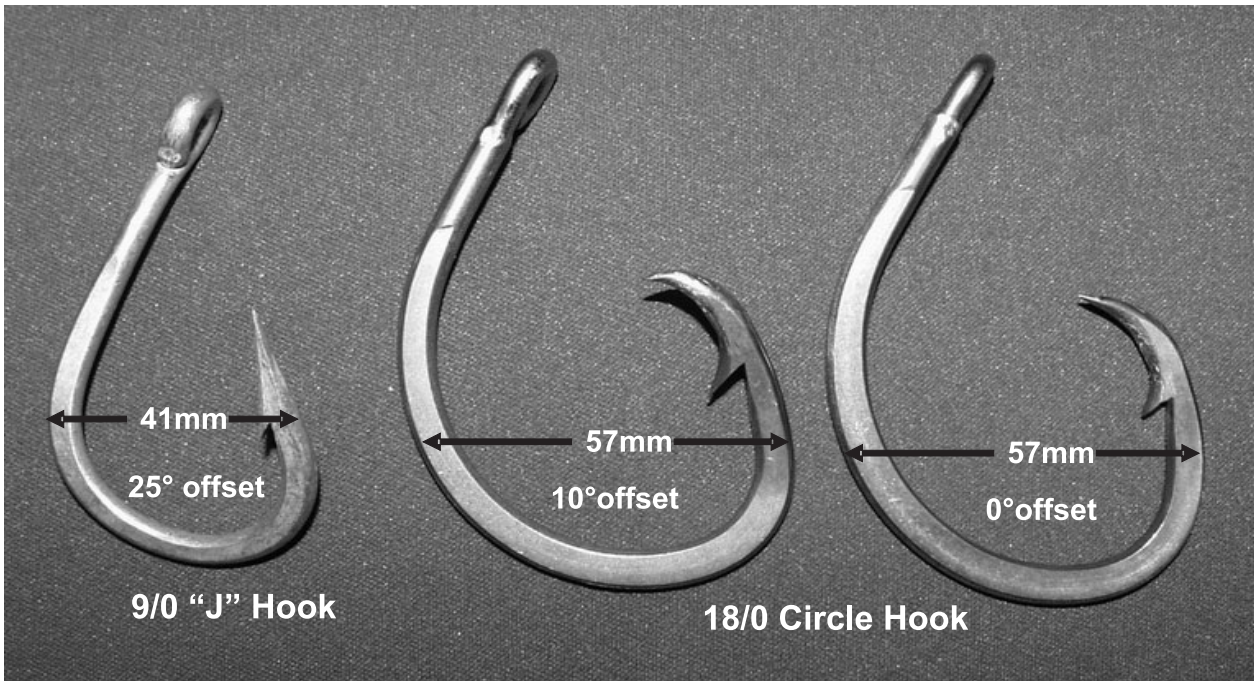
10% of the pelagic longline fishing effort in the North Atlantic Ocean (Witzell et al. 2001). Recent management actions by the United States were designed to reduce the impact of the United States pelagic longline fisheries on sea turtles in both the Pacific Ocean and Atlantic Ocean basins. Prime fishing grounds, including international waters of both the Pacific and Atlantic, have been closed to United States fishermen in an attempt to reduce incidental fishing mortality of sea turtles in the longline fishery (US Department of Commerce 1999, 2000). These actions have been legally contentious (Blue Water Fishermen's Association vs. National Marine Fisheries Service, 226 F. Supp. 2d 330 (D. Mass. 2002); Hawaii Longline Association vs. National Marine Fisheries Service, 281 F. Supp. 2d 1 (D.D.C. 2003)), and the outcomes are being scrutinized by the international fishing community, nongovernmental organizations, and foreign governments.

The Northeast Distant (NED) statistical reporting area in the Western North Atlantic (Fig. 1), including the productive Grand Banks, was closed to the United States fleet, partly in 2000 and completely during 2001–2003, as a result of interactions with threatened and endangered loggerhead and leatherback sea turtles (US Department of Commerce 2000, 2001*a*, 2001*b*). Our research focused first on eliminating or reducing interactions between the swordfish fishery and sea turtles. Second, for those interactions that could not be avoided, we strove to reduce the likelihood of sea turtles being injured or killed during or as a result of the interaction. There are many possible avenues for research to reduce sea turtle bycatch and mortality. Some may focus on the behavior of bycatch species, while others involve efforts to physically limit capture. We focused on the latter course of study and investigated the effects of hook style and bait.

The predominant hook type used historically in the United States Western Atlantic pelagic longline fishery for swordfish is the 9/0 J hook with 20°–25° offset (Fig. 2), and the predominant bait is squid (*Illex* spp.) (Hoey and Moore 1999). Offset hooks are hooks with the point bent sideways (usually 18°–20°) in relation to the shank. Offset hooks are believed to be more effective in hooking and retaining fish than a straight (0° offset) hook and are easier to bait. Recent studies have shown that circle style hooks with no offset or minor offset (about 4°) cause less physical damage to fish than J style hooks because of the tendency of circle hooks to engage fish in the mouth rather than in the pharynx, esophagus, or stomach and also because circle hooks minimize foul hooking (externally hooked) and bleeding (Prince et al. 2002; Skomal et al. 2002). Circle hook use in pelagic longline fisheries may increase the catch per unit effort (CPUE) of yellowfin tuna (*Thunnus albacares*) and improve the survival of incidental fish bycatch (Hoey 1996; Falterman and Graves 2002). With respect to sea turtles, a study conducted in the Azores found that 0° offset 16/0 circle hooks significantly decreased the proportion of swallowed hooks in loggerhead turtles but did not reduce the rate of turtle interaction (Bolten et al. 2002). Loggerhead turtle interactions observed include swallowed hooks, mouth hooked, hooked externally, and entangled. In 2001, leatherback turtle interactions in the Canadian longline fishery (Canadian Atlantic waters and NED) were higher with J hooks than with 10° offset 16/0 circle hooks (Javitech 2002). In this same study, interaction rates were lower for both leatherback and loggerhead turtles with mackerel (*Scomber scombrus*) bait versus squid bait (Javitech 2002).

In 2001 and 2002, we conducted research in the NED to evaluate the effects of pelagic longline fishing gear modifications. In 2002, we focused the research on hook style and bait. The goal of the research was to investigate methods to reduce turtle captures and turtle mortalities, while retaining viable fishing performance by the longline fleet. We also

Fig. 2. Control (9/0 J hook with 25° offset) and experimental (18/0 circle hook with 0° offset and 18/0 circle hook with 10° offset) hook designs.



evaluated the effects of these modifications on the bycatch species most frequently discarded by the United States fleet, blue shark (*Prionace glauca*), which is a target species in some fisheries around the world.

Materials and methods

Experimental design

We evaluated the effectiveness of circle hooks (C) versus J hooks (J) and mackerel (M: *Scomber scombrus*) bait versus squid (S: *Illex* spp.) bait in reducing the sea turtle interaction rate and injury associated with pelagic longline gear. The control treatment was the industry standard 20°–25° offset J hooks with squid bait (JS). Four experimental treatments were tested: (*i*) 0° offset 18/0 circle hooks with squid bait (C_1S), (*ii*) 10° offset 18/0 circle hooks with squid bait (C_2S), (*iii*) 20°–25° offset 9/0 J hooks with mackerel bait (JM), and (*iv*) 10° offset 18/0 circle hooks with mackerel bait (C_2M). Offset hooks were included among the treatments because it is difficult to bait the 0° offset 18/0 circle hooks with mackerel. The experimental treatments hooks were from a single manufacturer, Lindgren-Pitman Inc. (Pompano Beach, Florida) (LP).

Control and experimental hooks were alternated on each longline section (length of mainline between highflyer buoys) along the entire set. Only one bait type was used within a set to avoid possible interaction effect of bait types. Vessels alternated among the three experimental set configurations. On every set, vessels deployed the gear with three hooks fished between each set of floats: one placed directly adjacent to each float, and the other two placed between the floats at an equal distance from each other.

Fishing gear was standardized among the vessels to reduce gear-induced variability. Hook spacing was consistent within a trip, and a hook was fished adjacent to each float. Buoy lines, leader lengths and size, mainline, buoy line, and leader color were consistent within a trip. Green light sticks and leaded swivels were used on every leader, and placement was consistent. Bait used was 150–300 g squid bait or 200–500 g mackerel bait, and baiting technique was consistent within a trip. Control hooks were Mustad 9/0 #7698 RD, Mustad 9/0 #76801 (O. Mustad & Son, A.S., Gjövik, Norway), Eagle Claw 9/0 #9016 (Eagle Claw Fishing Tackle Co. Denver, Colorado), or LP-SW 9/0.

Setting time was restricted to no earlier than sunset, and captains attempted to have the gear hauled between 1000 and 1300 Eastern Standard Time. Other than the experimental design requirements, captains were allowed to fish normally and chose the location of fishing, length of trips, total number of hooks fished, etc. Fishing locations, length of trips, number of hooks fished, and catch rates were similar to those of observed trips prior to closure of the NED area to United States fishing vessels in 2000 (Hoey and Moore 1999; Beerkircher et al. 2002).

We conducted a power analysis to estimate the experimental fishing effort required to detect a fishing method that has different degrees of effectiveness in reducing bycatch of turtles in comparison with the control fishing method (Appendix A). The number of hooks required to detect a 25% and 50% reduction in loggerhead CPUE was 54 054 and 9012 hooks per treatment, respectively. Comparative efforts required for leatherback turtles were 163 548 and 26 828 hooks per treatment, respectively.

Data collection

All vessels participating in the experiment carried observers, and both the observers and the captains were well versed on the experimental design. Each observer was trained in safety; fish, mammal, and seabird identifications; data collection, and the operation of a pelagic longline fishing ves-

sel; many had prior experience. Observers also received extensive training on sea turtles: safe handling, collection of biological data, gear removal, tagging, etc.

Observers collected fishery data as described by the Southeast Fisheries Science Center (SEFSC) Pelagic Longline Observer Program (Beerkircher et al. 2002), with minor modifications to accommodate the experiment. Details on the Pelagic Observer Program are available online at http://www.sefsc.noaa.gov/pop.jsp. The time and location of each section of gear was recorded as it was deployed and retrieved, as was the sea surface temperature. These data were obtained from the vessel's existing wheelhouse equipment and were reported in nonmetric units. The section number, treatment (hook type and style), time on deck, and species were recorded for each animal captured. If boated, length was measured in centimetres. Length was estimated for marine mammals, which were not boated. A carcass tag applied to each fish was used to match the dressed weight (carcass with head and fins removed and animal eviscerated) of the fish during unloading at the dock to the particular data collected on that animal at sea.

For sea turtles, the type of interaction (hooked, entangled, or hooked and entangled), the exact location of the hook in the turtle, and the hook style was recorded. The protocols for collecting sea turtle capture data are available online at http://www.sefsc.noaa.gov/seaturtlefisheriesobservers.jsp. In addition, time, sea surface temperature, location, and the position of turtle (section and hook position relative to a buoy) within the set were noted. Carapace lengths of turtles not boated (leatherbacks) were estimated. Observers and crew attempted to remove fishing gear using long-handled dehookers and line cutters. When possible, turtles (loggerheads) were boated with a large dip net. Observers attempted to remove all gear immediately. They were instructed to remove all external hooks and those in the mouth, as well as hooks in the esophagus when the insertion point of the barb could be seen. Boated turtles were measured to the nearest 0.1 cm and tagged. Details about any gear remaining on the animal at time of release were noted, in addition to the turtle's condition, the time, location, and sea surface temperature.

Statistical methods

The relationship between the catch rate (or catch probability) and the explanatory variables (hook type, sea surface temperature, daylight soak time, and total soak time) was investigated using generalized linear models (Agresti 1996; Draper and Smith 1998; Hosmer and Lemeshow 1989). In particular, logistic regression analysis (with maximum likelihood estimation procedure) for binary response (turtle and blue shark) count data and traditional regression analysis (with least squares estimation procedure) for continuous response weight data was used. (Swordfish and bigeye tuna (*Thunnus obesus*) were retained for sale.) There were some animals caught for which a treatment (hook type) could not be determined; these included animals that were hooked with both control and treatment hooks and animals that were entangled (not hooked). These data were excluded from the analysis. Section sea surface temperatures and hook soak time measurements were averaged for each set. Total soak time and daylight soak time values were estimated by averaging the soak times for the beginning and end of each section. Sunrise and sunset values were obtained for centralized locations within the fishing area using software provided by the Astronomical Applications Department of the US Naval Observatory. Sunrise and sunset estimates are within 20 min of actual times. The effect of hook depth was not examined, since swordfishers set fish hooks at approximately the same depth.

The modeling results presented used set as the experimental unit. A test of coincidence of the models was performed, and the treatments were combined where appropriate. The confidence intervals (CIs) on appropriate model coefficients (or its functions) were constructed to arrive at the CIs on reduction rate for each of the treatments. All analyses utilized the original units of measurements (e.g., dressed weight and sea surface temperature).

Since the probability of a turtle catch (per hook) for the hook types being compared is fairly small, the catch probability ratio for the two hook types was approximated from the odds ratio (corresponding to hook types) estimated from the fitted logistic regression models. Thus, subtracting the odds ratio (and confidence limits) from 1 provides an estimate of reduction rate (and related confidence limits) due to experimental hook. Approximation of relative risk for other factors also utilized odds ratio owing to low magnitude of catch probability. For swordfish and bigeye tuna, where catch weight per hook is modeled through traditional regression techniques, a CI on absolute weight reduction (per hook) was constructed. The limits of this CI were then divided by average catch per control hook to estimate CIs for reduction rate. The ratio is a natural scale for multiplicative models, while the difference is a natural scale for additive models. Thus, ratio of odds (of turtle capture for control and experimental hooks) is a natural scale for the logistic models, while the difference in the means (of catch per hook for the control and experimental hooks) is a natural scale for the traditional regression model for continuous response variable. Chi-square tests were used to compare hook locations in sea turtles among hook types and bait types.

Results

During July–October 2002, 13 commercial longline vessels made 489 research sets in the NED, fishing a total of 427 382 hooks: approximately 142 000 for the control (J hooks with squid bait) and about 71 000 hooks for each treatment. Vessels fished an average of 874 hooks per set; the minimum number of hooks fished in a set was 210 hooks, and the maximum was 1173 hooks. The average number of sections per set was eight and the range was 2–11. The spatial and temporal distribution of the sets by hook and bait type and the mean sea surface temperature among treatments were the same (Figs. 3 and 4). The combined length of float lines and gangions was between 11.0 and 23.8 m, which represents the approximate depth of the hooks, excluding curvature of mainline. Soak times ranged from 524 to 1556 min, with an average of 761 min and standard deviation of 99 min, while temperature ranged from 12 to 23 °C, with an average of 17 °C and standard deviation of 1.7 °C. The vessels caught 34 taxa of fish (Table 1). The target species, swordfish and bigeye tuna, along with blue

Fig. 3. Geographical effort distribution by bait type. Circles represent sets using mackerel (*Scomber scombrus*) bait; triangles represent sets using squid (*Illex* spp.) bait. Grayscale represents depth contours.

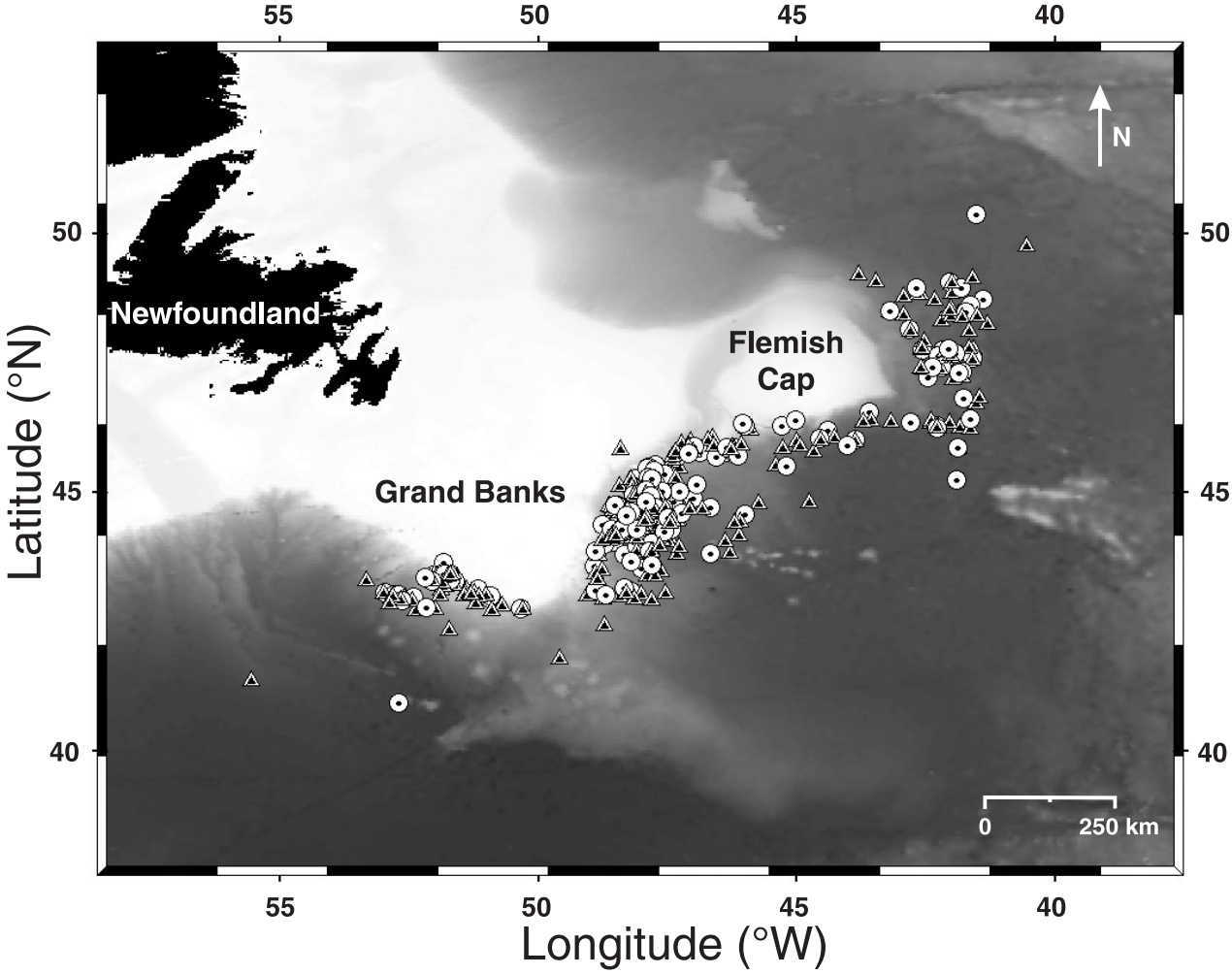
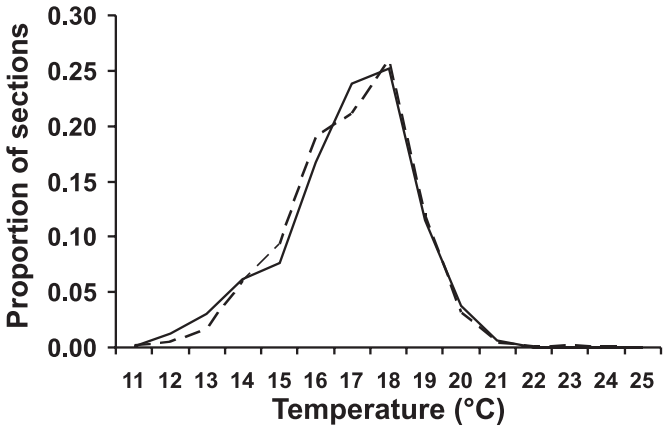


Fig. 4. Sea surface temperature distribution (mean section temperature) by bait type. Solid line represents temperatures at which mackerel (*Scomber scombrus*) bait were fished; broken line represents temperatures at which squid (*Illex* spp.) bait were fished.



shark, were the species most often caught. The vessels kept for sale 7925 swordfish (total dressed weight of 399.2 tonnes (t)) and 864 bigeye tuna (total dressed weight of 30.8 t). Blue shark was the species most frequently captured, but few (n = 8, total dressed weight = 0.2 t) were kept. During the course of the experiment, 96 loggerhead and 148 leatherback turtles were captured and released alive (original data shown in National Research Council Data Depository (NRC-DD) Table S1[2]). The vessels also captured 12 seabirds and nine marine mammals: five unidentified seabirds (one estimated at 120 cm in length), three greater shearwaters (*Puffinus gravis*, 60–75 cm), three *Puffinus* spp.(one 65 cm in length), one northern gannet (*Sula bassanus*), four Risso's dolphins (*Grampus griseus*, 1.5–2.4 m), two *Stenella* spp. (1.5–1.7 m), one common dolphin (*Delphinus delphis*, 2.1 m), one pilot whale (*Globicephala* spp., 1.8 m), and one unidentified marine mammal (6 m). All mammals were released alive, as were the northern gannet, one *Puffinus* spp., and three unidentified seabirds.

[2] Supplementary data for this article are available on the Web site or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0S2, Canada. DUD 3659. For more information on obtaining material refer to http://cisti-icist.nrc-cnrc.gc.ca/irm/unpub_e.shtml.

Table 1. Fish and sharks caught on experimental pelagic longline sets.

Scientific name	Common name	Discarded	Kept
Prionace glauca	Blue shark	12 747	8
Xiphius gladius	Swordfish	1 338	7 925
Thunnus obesus	Bigeye tuna	60	864
Thunnus alalunga	Aalbacore	180	233
Isurus oxyrinchus	Shortfin mako	144	191
Lamna nasus	Porbeagle	257	16
Thunnus thynnus	Bluefin tuna	76	30
Alepisaurus spp.	Lancetfishes	98	1
Rajiformes	Skates, rays, sawfishes, and guitarfishes	91	
Coryphaena spp.	Dolphins	37	7
Unknown	—	42	
Mola spp.	Molas	20	
Ruvettus pretiosus	Oilfish	19	1
Squaliformes	Dogfish and angel sharks	16	
Lepidocybium flavobrunneum	Escolar	13	1
Tetrapturus albidus	White marlin	8	
Trichiuridae	Snake mackerels	8	
Thunnus albacares	Yellowfin tuna	1	2
Thunnus spp.	Tunas and albacore	3	
Isurus paucus	Longfin mako	2	
Makaira nigricans	Blue marlin	2	
Polyprion americanus	Wreckfish	2	
Somniosus microcephalus	Greenland shark	2	
Tetrapturus georgei	Roundscale spearfish	2	
Tetrapturus spp.	Marlins and spearfish	2	
Acanthocybium solandri	Wahoo		1
Alopias spp.	Thresher sharks	1	
Alopias superciliosus	Bigeye thresher	1	
Brama spp.	Pomfrets	1	
Cetorhinus maximus	Basking shark	1	
Isurus spp.	Mako sharks	1	
Katsuwonus pelamis	Skipjack tuna	1	
Lophius americanus	Goosefish	1	
Tetrapturus pfluegeri	Longbill spearfish	1	

Treatment effects

Loggerhead sea turtles

Loggerheads ranged in size from 32.4 to 68.0 cm standard straight line carapace length (SCL_{std}) and averaged 56.8 cm (n = 93) (Fig. 5*a*). No loggerheads had been tagged previously. The highest reduction rates for loggerhead turtle interaction with pelagic longline gear, when compared with the traditional J hook and squid bait used in this fishery, was achieved with 18/0 circle hooks with mackerel bait. Circle hooks used in combination with mackerel bait reduced loggerhead catch by 90% (CI = 70%–97%, $p < 0.0001$). Circle hooks with squid bait reduced loggerhead catch by 86% (CI = 73%–93%, $p < 0.0001$) and mackerel bait with J hooks by 71% (CI = 42%–86%, $p = 0.0005$) (Fig. 6*a*). The odds ratio ranged from 0.10 to 0.29 in these models, suggesting the loggerhead turtle catch on the control hook and bait was between 3.4 and 10 times (increase of 240%–900%) that of the experimental hooks and bait (Table 2).

The sea surface temperature effect for loggerhead turtles also was highly significant ($p < 0.0001$). The loggerhead turtle catch rate increased by a multiplicative factor of 25%–35% with 0.6 °C increase in sea surface temperature. Thus, the loggerhead catch rate increased 200%–350% with every 2.8 °C increase in sea surface temperature. Extrapolations of effects of sea surface temperature outside the range observed were not appropriate.

The effect of total soak time on loggerhead turtle catch was highly significant ($p \leq 0.0003$) as well, suggesting an increase in the loggerhead turtle catch rate by a multiplicative factor of 0.6%–0.8%, with a unit increase (min) in total soak time. The effect of daylight soak time (a portion of the total soak time) was varied and inconclusive (p values ranging from 0.0008 to 0.5822). We suspect that there was a confounding effect between total soak time and daylight soak time. Swordfish sets were made at sunset and retrieved early in the morning, which means any increase in total soak time was an increase in daylight soak time. The odds ratios ranged between 0.987 and 0.999.

Circle hooks also resulted in a significant change in hooking location ($p < 0.01$). Loggerheads most often were hooked internally, although foul hooking sometimes occurred. The majority (68.8%, n = 55) of the 80 loggerheads caught on J hooks swallowed the hooks (Fig. 7*a*), which probably is the most lethal form of hooking interaction. In contrast, only 27.3% (n = 3) of the 11 loggerheads caught on

Fig. 5. Carapace lengths of (*a*) loggerhead turtles (*Caretta caretta*; *n* = 93) and (*b*) leatherback turtles (*Dermochelys coriacea*; *n* = 147).

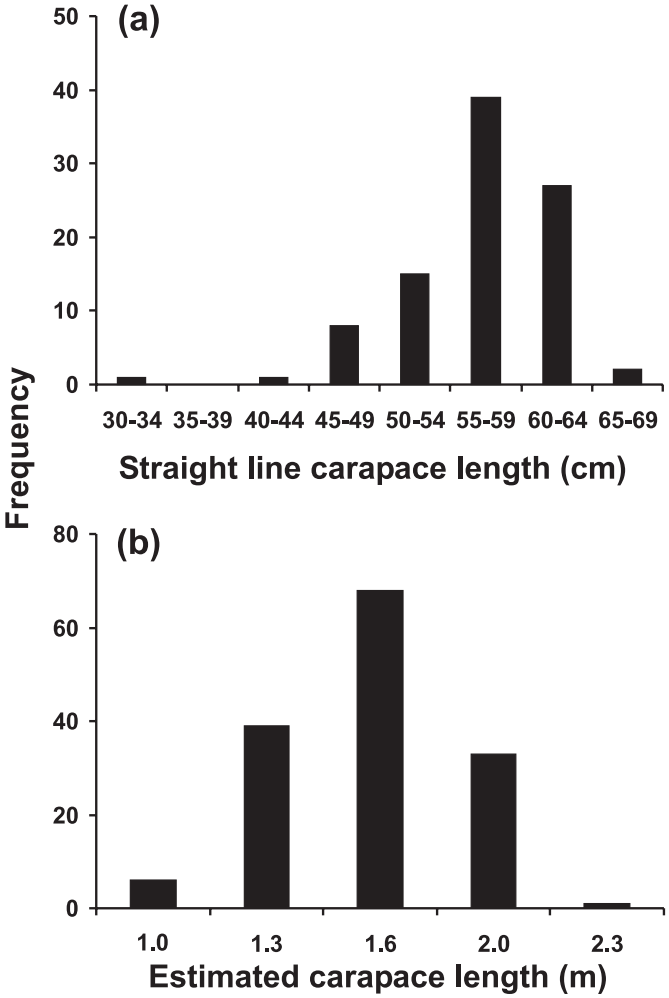
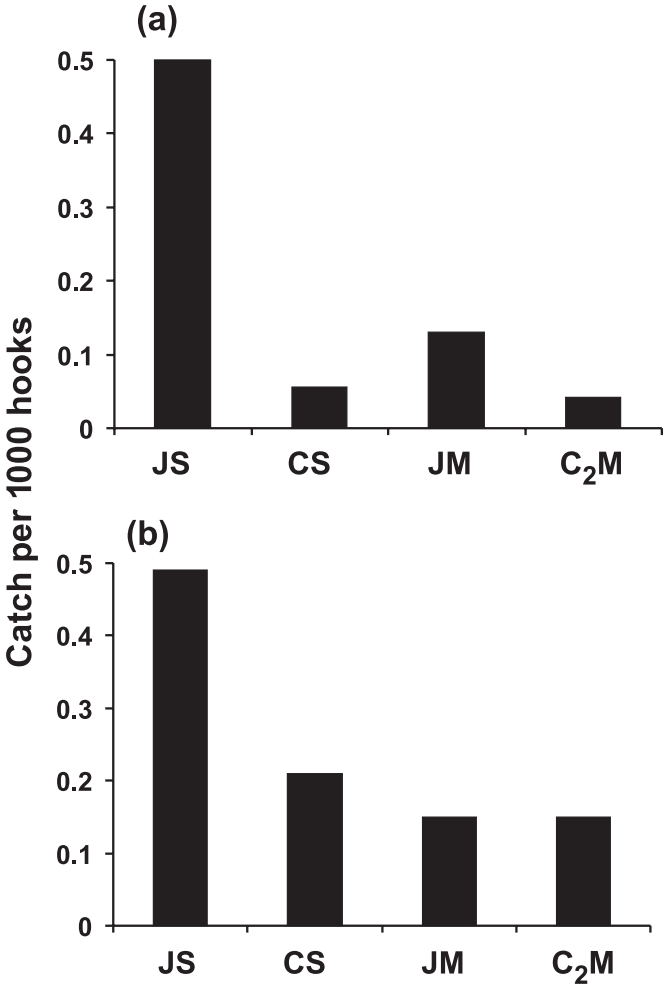


Fig. 6. Catch per unit effort for (*a*) loggerhead turtles (*Caretta caretta*) and (*b*) leatherback turtles (*Dermochelys coriacea*) caught on (*i*) 25° offset 9/0 J hooks using squid bait (*n* = 142 701) (JS), (*ii*) 0° and 10° offset 18/0 circle hooks combined using squid bait (*n* = 142 701) (CS), (*iii*) 25° offset 9/0 J hooks using mackerel bait (*n* = 70 990) (JM), and (*iv*) 10° offset 18/0 circle hooks using mackerel bait (*n* = 70 990) (C_2M).



circle hooks swallowed the hooks; most were hooked in the mouth, where the hooks could be removed more safely (Fig. 7*a*). There was no significant difference in hooking location of loggerheads between hooks baited with mackerel and hooks baited with squid ($p > 0.5$). Sample size was too small to statistically evaluate the effects of hook offset or the interaction of bait and hook type on the hooking location.

Leatherback sea turtles

The estimated carapace lengths of leatherbacks ranged from 1.0 to 2.3 m, with a mode of 1.6 m (*n* = 147) (Fig. 5*b*). The largest reduction in leatherback turtle catch rate was achieved with mackerel bait. The J hooks with mackerel bait reduced leatherback catch by 66% (CI = 37%–81%, p = 0.0006), and circle hooks with mackerel bait reduced leatherback catch by 65% (CI = 36%–81%, p = 0.0007) (Fig. 6*b*). Circle hooks with squid bait reduced leatherback turtle catch by 57% (CI = 34%–72%, $p < 0.0001$) (Table 3). The leatherback turtle catch rate on the control hook and bait was 2.0–2.9 times (increase of 100%–190%) that of the experimental hooks and bait (the odds ratios ranged from 0.34 to 0.50).

The sea surface temperature effect for leatherback turtles was also highly significant ($p \leq 0.0095$). The leatherback catch rate increased by a multiplicative factor of 14%–22%, with a 0.6 °C increase in sea surface temperature. Neither total soak time nor daylight soak time had a significant effect on leatherback catch rates ($p \geq 0.1761$ and $p \geq 0.6421$, respectively). This difference compared with loggerhead turtles may indicate a difference in time of interaction between these two species.

In contrast with loggerheads, the change in hooking location with treatments was not as pronounced. Leatherbacks most often were hooked externally or were entangled in the lines (Fig. 7*b*); often they were both hooked and entangled (*n* = 23). They mostly were hooked in the shoulder, armpit, or front flipper (*n* = 107); rarely was the hook internal (*n* = 8). The comparison of hook locations between the two bait types was not significant ($p > 0.10$). However, there was a significant difference in hooking location between hook types ($p < 0.0001$; Fig. 7*b*). With circle hooks, a signifi-

Table 2. Odds ratio estimates from the models for loggerhead (*Caretta caretta*) turtles.

Effect	Odds ratio	95% Wald confidence limits		*p*
Treatment C_1S (0° offset 18/0 circle hook with squid bait)				
Hook type	0.125	0.044	0.352	<0.0001
Sea surface temperature	1.348	1.253	1.449	<0.0001
Total soak time	1.007	1.003	1.011	0.0003
Daylight soak time	0.987	0.979	0.995	0.0008
Treatment C_2S (10° offset 18/0 circle hook with squid bait)				
Hook type	0.15	0.064	0.353	<0.0001
Sea surface temperature	1.245	1.134	1.367	<0.0001
Total soak time	1.008	1.004	1.011	0.0001
Daylight soak time	0.999	0.993	1.004	0.5822
Treatment CS (C_1S and C_2S combined)				
Hook type	0.139	0.072	0.269	<0.0001
Sea surface temperature	1.287	1.216	1.362	<0.0001
Total soak time	1.006	1.004	1.008	<0.0001
Daylight soak time	0.994	0.990	0.998	0.0051
Treatment JM (25° offset J hook with mackerel bait)				
Hook type	0.291	0.145	0.585	0.0005
Sea surface temperature	1.276	1.204	1.353	<0.0001
Total soak time	1.006	1.004	1.009	<0.0001
Daylight soak time	0.993	0.988	0.997	0.001
Treatment C_2M (10° offset 18/0 circle hook with mackerel bait)				
Hook type	0.096	0.030	0.305	<0.0001
Sea surface temperature	1.276	1.201	1.355	<0.0001
Total soak time	1.006	1.004	1.008	<0.0001
Daylight soak time	0.993	0.993	0.998	0.0024

Note: Sea surface temperature data were modeled in degrees Fahrenheit; soak times were were modeled in minutes.

cantly larger proportion (of a smaller number) were not hooked externally and instead were getting the bait into their mouth (Fig. 7*d*); seven of eight leatherbacks hooked in the mouth were taken on circle hooks (six of seven on the circle hook with a 10° offset), and seven of the eight were taken on squid. Sample size was too small to statistically evaluate the effects of hook offset or the interaction of bait and hook type on the hooking location.

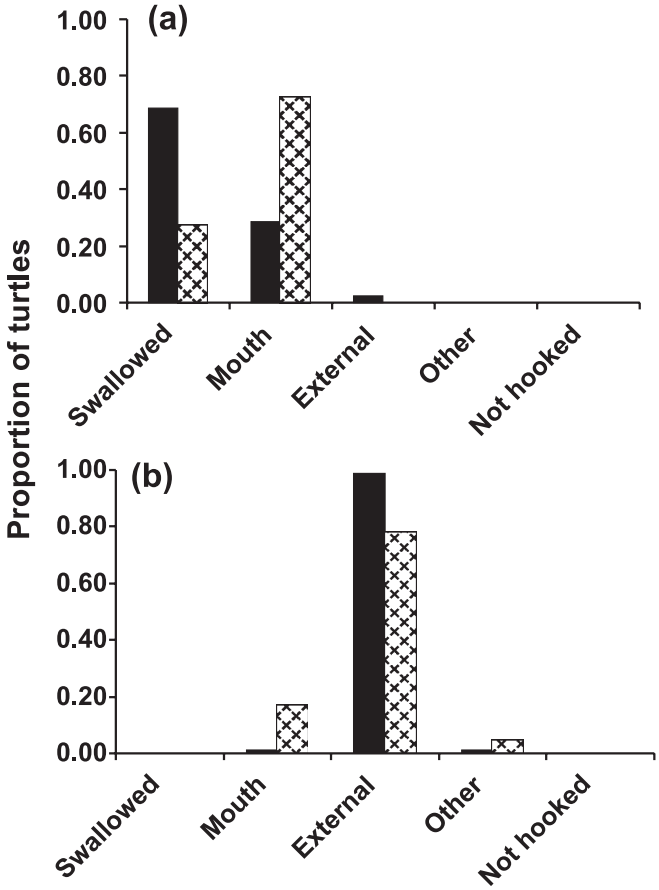
Swordfish

Swordfish is the primary target species in the NED fishery studied. Swordfish caught averaged 164 cm in length (range 57–283 cm), and the mean weight of swordfish retained was 50.1 kg (range 10.9–245.5 kg). Swordfish catch rate was increased 30% (CI = 14%–46%, $p = 0.0002$) by circle hooks with mackerel bait and 63% (CI = 46%–81%, $p < 0.0001$) by J hooks with mackerel bait. The catch rate of swordfish was reduced 33% (CI = 19%–46%, $p < 0.0001$) by 0° offset circle hooks with squid bait (C_1S) and 29% (CI = 14%–44%, $p = 0.0002$) by 10° offset circle hooks with squid bait (C_2S) (Fig. 8*a*). The models for treatments C_1S and C_2S could not be combined for swordfish because of a significant difference between the two models ($p = 0.0005$). Both circle hook types (C_1 and C_2) and mackerel bait significantly ($p = 0.0002$) affected swordfish catch (Table 4).

The sea surface temperature effect for swordfish was found to be significant only in the models for the circle hooks baited with squid treatments (C_1S, $p = 0.0413$; C_2S, $p = 0.0441$). The respective regression coefficients of 0.046 and 0.060 indicate an increase of between 20.9 and 27.2 kg of swordfish catch per 1000 hooks per 0.6 °C increase in sea surface temperature. The effect of total soak time on swordfish catch was not significant ($p \geq 0.0629$). However, the effect of daylight soak time was positive and significant ($p \leq 0.0279$). The positive relationship between daylight soak time and swordfish catch is most likely spurious, because swordfish are caught on longline gear at night (Hoey and Moore 1999). A probable explanation of this positive relationship is that daylight soak time is related to haul time, which increases as nighttime swordfish catch increases because of the increased time required for handling and processing the catch.

The mouth was the most frequent location of hooks in swordfish caught in the control and each treatment. However, hooking location proportions did vary among the treatments. Differences among treatments were mainly due to a shift between gut and mouth hooking. Both circle hooks, baited with squid and with mackerel (11%–18%) and mackerel alone (24%), resulted in less gut hooking than J hooks baited with squid (30%) ($p < 0.0001$) (original data shown in NRC-DD Table S2[2]). Gut hooking was more frequent with the 10° offset circle hook (18%) than with the 0° offset circle hook (12%) when baited with squid ($p < 0.0001$), but still was less than with J hooks. The observed reduction in swordfish catch with circle hooks is believed to be due to the increased percentage of mouth-hooked fish and the tendency

Fig. 7. Location of hooks in (*a*) loggerhead turtles (*Caretta caretta*) caught on J hooks (solid bars) (n = 80) and 18/0 circle hooks (hatched bars) (n = 11) and (*b*) leatherback turtles (*Dermochelys coriacea*) caught on J hooks (n = 82) and 18/0 circle hooks (n = 40). Note that the totals reported are fewer than the total number of animals captured (loggerheads n = 96 and leatherbacks n = 148) because some animals were not hooked or hook type was unknown or they were caught with more than one hook.



of hooks to pull out of the relatively weak jaw structure of swordfish. Fishers have also reported that a larger percentage of swordfish are alive and active when using circle hooks, as compared with J hooks, and that the fish quality is better.

Bigeye tuna

Bigeye tuna are a secondary target catch in the fishery and are retained for sale. Bigeye tuna caught averaged 130 cm in length (range 70–181 cm) and the mean weight of retained fish was 35.3 kg (range 11.8–87.7 kg). Circle hooks baited with squid increased the catch rate of bigeye tuna (26%), but the increase was not significant (p = 0.1463). Mackerel bait significantly reduced the catch rate of bigeye tuna on both 18/0 circle hooks (81%, CI = 49%–100%, p < 0.0001) and J hooks (90%, CI = 58%–100%, p < 0.0001) (Fig. 8*b*).

The sea surface temperature effect for bigeye tuna was highly significant (p < 0.0001) (Table 5). Bigeye tuna catch rates increased between 10.9 and 18.1 kg per 1000 hooks for every 0.6 °C increase in sea surface temperature (the regression coefficients for temperature varied between 0.024 (for treatments JM and C_2M) and 0.040 (for treatments C_1S, C_2S, and CS)). The effect of total soak time on bigeye tuna catch was significant ($p \leq 0.0176$), but the effect of daylight soak time was not ($p \geq 0.1101$), which may again be related to the confounding effects of total soak time and daylight soak time.

The majority of bigeye tuna were hooked in the mouth (91%–100%) regardless of hook type or bait type (orginal data shown in NRC-DD Table S3[2]), but there was significantly more gut hooking (8%) (p < 0.005) with J hooks baited with squid than with circle hooks (2%). There was no significant effect on hook location by mackerel or by circle hook offset (p > 0.05).

Blue shark

Blue shark is primarily a bycatch species in the United States Atlantic longline fishery, but is a target species in some other fisheries (Hazin et al. 2002). The catch rate of blue sharks was increased 8% (CI = 2%–14%, p < 0.0073) by 0° offset circle hooks (C_1S) with squid bait and 9% (CI = 3%–16%, p = 0.0030) by 10° offset circle hooks (C_2S) with squid bait (Fig. 8*c*). The models for treatments C_1S and C_2S could not be combined for blue sharks because of a major difference between the two. Mackerel bait reduced the catch of blue sharks on both 18/0 circle hooks (31%, CI = 27%–35%, p < 0.0001) and J hooks (40%, CI = 36%–43%, p < 0.0001) (Fig. 8*c*).

The sea surface temperature effect for blue shark was highly significant (p < 0.0001) (Table 6). The blue shark catch rate decreased by a multiplicative factor of 9.7%–11.4% with 0.6 °C increase in sea surface temperature (odds ratio varied from 0.886 to 0.903), depending on the treatment comparison.

The effect of total soak time of the hooks on blue shark catch was statistically significant (p < 0.002), but the effect was too small to be of practical importance. The odds ratio was very close to 1.000 (ranged between 0.999 and approximately 1.000). We suspect that there was a confounding effect between total soak time and daylight soak time. The effect of daylight soak time was highly significant (p < 0.0001) and fairly consistent in the four models fitted. In each model, the odds ratio was 1.005. Thus, the blue shark catch rate increased by a multiplicative factor of 0.5% with a unit increase (min) in daylight soak time. This means that blue shark catch rate increased by 16% with every 30 min increase in daylight soak time.

Hooking location in blue sharks varied by hook type, and for J hooks, by bait; circle hook offset also was significant. Blue sharks were hooked more frequently in the gut with 9/0 J hooks (25%–32%) compared with 18/0 circle hooks (10%–12%; p < 0.0001; original data shown in NRC-DD Table S4[2]). Mackerel increased the gut hooking with J hooks (35% vs. 25%) (p < 0.0001), but not with circle hooks (p > 0.25). Circle hook offset also resulted in a greater gut hooking (p < 0.0001), but still was less than that with J hooks.

Removal of gear

Hooks and line were removed from many of the sea turtles with the tools provided to the vessels; these same tools were also used to remove gear from marine mammals and sometimes from other bycatch species, such as *Mola* spp., and blue shark. Detailed information on the amount of gear

Table 3. Odds ratio estimates from the models for leatherback (*Dermochelys coriacea*) turtles.

Effect	Odds ratio	95% Wald confidence limits		*p*
Treatment C_1S (0° offset 18/0 circle hook with squid bait)				
Hook type	0.361	0.191	0.681	0.0016
Sea surface temperature	1.201	1.102	1.309	<0.0001
Total soak time	1.001	0.998	1.004	0.4332
Daylight soak time	1.001	0.996	1.005	0.7772
Treatment C_2S (10° offset 18/0 circle hook with squid bait)				
Hook type	0.5	0.284	0.880	0.0163
Sea surface temperature	1.144	1.033	1.266	0.0095
Total soak time	0.998	0.994	1.002	0.3049
Daylight soak time	1.001	0.996	1.006	0.7618
Treatment CS (C_1S and C_2S combined)				
Hook type	0.43	0.282	0.656	<0.0001
Sea surface temperature	1.178	1.102	1.259	<0.0001
Total soak time	1	0.998	1.002	0.9324
Daylight soak time	1.001	0.997	1.004	0.6421
Treatment JM (25° offset J hook with mackerel bait)				
Hook type	0.344	0.187	0.634	0.0006
Sea surface temperature	1.184	1.096	1.280	<0.0001
Total soak time	0.998	0.995	1.001	0.1761
Daylight soak time	1	0.996	1.005	0.8257
Treatment C_2M (10° offset 18/0 circle hook with mackerel bait)				
Hook type	0.346	0.187	0.637	0.0007
Sea surface temperature	1.219	1.130	1.314	<0.0001
Total soak time	0.999	0.996	1.002	0.366
Daylight soak time	1	0.996	1.004	0.8863

Note: Sea surface temperature data were modeled in degrees Fahrenheit; soak times were were modeled in minutes.

remaining at release was recorded only for sea turtles and marine mammals. All gear was removed from three of the marine mammals; the fishers attempted to remove gear from the other animals, but they were released with the hook and some line still attached. For loggerheads, 7 of the 58 swallowed hooks were removed, along with all other hooks located in the mouth or externally, except for one lodged in the glottis (Table 7). A small amount of line was left on some hooks that had been swallowed (n = 31); usually the line remaining was <3 cm. Hooks were also retrieved from captured leatherbacks, which, except on two occasions, were not boated. One hundred thirty leatherbacks were hooked or possibly hooked. The hooks were recovered from 61 of these animals (information was not recorded for an additional five). This included six of eight hooks in the mouth (Table 7). All line was removed from 90 leatherbacks, and the line remaining on the rest usually (>50%) was less than 0.3 m.

Discussion

Loggerheads and leatherbacks, like all sea turtles, hatch from eggs laid on ocean beaches. Their life histories are very different in other respects, however, and pelagic longlines impact these species differently. Loggerheads have a distinct juvenile life stage that lives in the oceanic environment leading a pelagic existence (Carr 1987). After about 8–15 years, the young juveniles move to the neritic environment and become demersal (Bjorndal et al. 2000; Snover 2002), reaching maturity after nearly 20 years in that stage–environment (Snover 2002). There is some movement between the two habitats, at least during the period when the juveniles are transitioning to the neritic environment (Witzell 2002; Bolten 2003). Loggerheads captured on pelagic longlines in the NED are young, oceanic, pelagic animals or are those in transition and are the largest loggerheads in that environment (Bjorndal et al. 2003; S. Epperly, unpublished data). They may be either about to leave the oceanic environment or are transients, and this may explain why we did not recapture any turtles that were tagged during our experiments. In contrast, leatherbacks are pelagic animals living mostly in the oceanic environment (Pritchard and Trebbau 1984). Leatherbacks across a large range of sizes are captured on the longlines, including big animals comparable in size to nesting females of the Western North Atlantic (Boulon et al. 1996).

Pelagic longlines have been implicated as a major source of anthropogenic mortality for loggerhead and leatherback sea turtles (Lewison et al. 2004). The present study demonstrates that loggerhead and leatherback sea turtle interactions associated with the Western Atlantic pelagic swordfish longline fishery can be significantly reduced by employing 18/0 circle hooks or by using mackerel bait in place of squid bait. Importantly, when the two treatments are used in com-

Fig. 8. Catch per unit effort for (*a*) swordfish (*Xiphias gladius*), (*b*) bigeye tuna (*Thunnus obesus*), and (*c*) blue sharks (*Prionace glauca*) caught on (*i*) 25° offset 9/0 J hooks using squid (*Illex* spp.) bait (n = 142 701) (JS), (*ii*) 0° and 10° offset 18/0 circle hooks combined using squid bait (n = 142 701) (CS), (*iii*) 0° offset 18/0 circle hooks using squid bait (n = 71 931) (C_1S), (*iv*) 10° offset 18/0 circle hooks using squid bait (n = 70 700) (C_2S), (*v*) 25° offset 9/0 J hooks using mackerel (*Scomber scombrus*) bait (n = 70 990) (JM), and (*vi*) 10° offset 18/0 circle hooks using mackerel bait (n = 70 990) (C_2M).

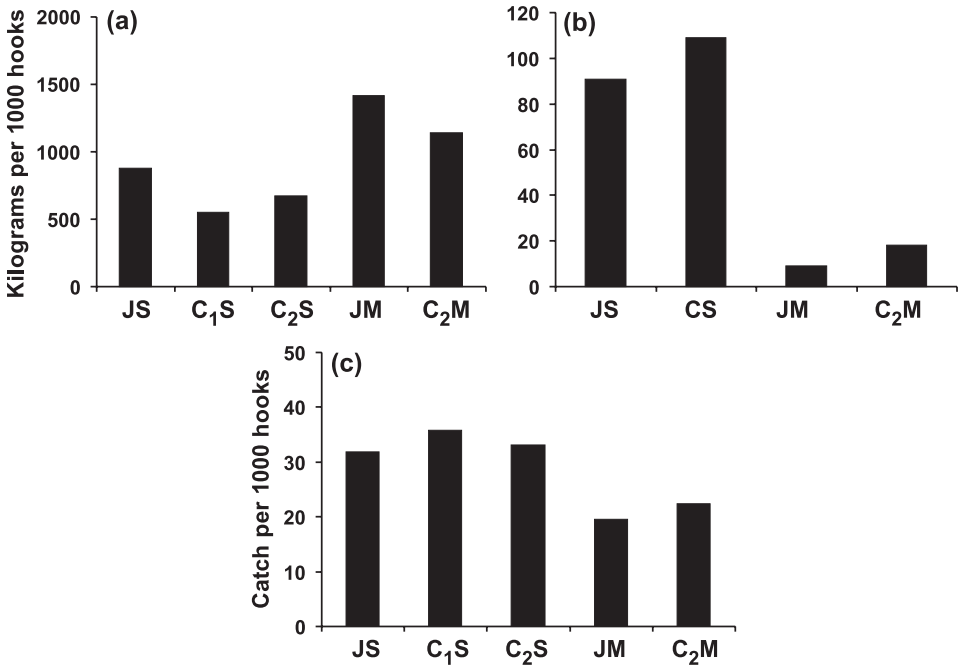


Table 4. Odds ratio estimates from the models for swordfish (*Xiphias gladius*).

Effect	Odds ratio	95% Wald confidence limits		p
Treatment C_1S (0° offset 18/0 circle hook with squid bait)				
Hook type	–0.592	–0.842	–0.341	<0.0001
Sea surface temperature	0.046	0.002	0.090	0.0413
Total soak time	–0.001	–0.002	0.001	0.2221
Daylight soak time	0.002	0.0002	0.004	0.0279
Treatment C_2S (10° offset 18/0 circle hook with squid bait)				
Hook type	–0.596	–0.912	–0.279	0.0002
Sea surface temperature	0.06	0.002	0.119	0.0441
Total soak time	0.002	–0.0001	0.004	0.0629
Daylight soak time	0.005	0.002	0.008	0.0007
Treatment JM (25° offset J hooks with mackerel bait)				
Hook type	1.235	0.894	1.576	<0.0001
Sea surface temperature	0.032	–0.027	0.090	0.2857
Total soak time	0.0004	–0.002	0.002	0.689
Daylight soak time	0.005	0.002	0.008	0.0005
Treatment C_2M (10° offset 18/0 circle hooks with mackerel bait)				
Hook type	0.589	0.276	0.902	0.0002
Sea surface temperature	0.034	–0.020	0.087	0.2148
Total soak time	0.0004	–0.001	0.002	0.669
Daylight soak time	0.005	0.003	0.008	0.0001

Note: Sea surface temperature data were modeled in degrees Fahrenheit; soak times were were modeled in minutes.

bination, the resulting reduction in turtle interactions — 90% for loggerheads and 65% for leatherbacks — can be obtained without negatively impacting swordfish catch on the Grand Banks.

The post-hooking survival of sea turtles is unknown, but a pilot study employing pop-off archival satellite tags was initiated during these experiments and is ongoing (Epperly et al. 2002, 2003). Harm from gear left in place may include

Table 5. Odds ratio estimates from the models for bigeye tuna (*Thunnus obesus*).

Effect	Odds ratio	95% Wald confidence limits		*p*
Treatment C_1S (0° offset 18/0 circle hook with squid bait)				
Hook type	0.063	–0.042	0.169	0.2403
Sea surface temp.	0.04	0.021	0.059	<0.0001
Total soak time	0.001	0.000	0.001	0.0176
Daylight soak time	0	–0.001	0.001	0.9086
Treatment C_2S (10° offset 18/0 circle hook with squid bait)				
Hook type	0.043	–0.054	0.140	0.3863
Sea surface temp.	0.038	0.020	0.056	<0.0001
Total soak time	0.002	0.001	0.002	<0.0001
Daylight soak time	–0.001	–0.002	0.000	0.1101
Treatment CS (C_1S and C_2S combined)				
Hook type	0.053	–0.019	0.125	0.1463
Sea surface temp.	0.038	0.025	0.051	<0.0001
Total soak time	0.001	0.001	0.002	<0.0001
Daylight soak time	0	–0.001	0.000	0.257
Treatment JM (25° offset J hooks with mackerel bait)				
Hook type	–0.184	–0.250	–0.118	<0.0001
Sea surface temp	0.024	0.012	0.035	<0.0001
Total soak time	0.001	0.000	0.001	<0.0001
Daylight soak time	0	–0.001	0.000	0.4019
Treatment C_2M (10° offset 18/0 circle hooks with mackerel bait)				
Hook type	–0.166	–0.232	–0.099	<0.0001
Sea surface temp.	0.025	0.014	0.036	<0.0001
Total soak time	0.001	0.001	0.001	<0.0001
Daylight soak time	0	–0.001	0.000	0.2144

Note: Sea surface temperature data were modeled in degrees Fahrenheit; soak times were were modeled in minutes.

tissue damage, infection, and digestive track blockage. Hooks may perforate internal organs or vessels; in some cases, hooks become encapsulated or are expelled. Trailing line can encircle a limb, restrict circulation, and cut deeply into the tissue, and eventually cause loss of function. Ingested line may irritate the lining of the gastrointestinal tract and cause death by torsion (involution) or intussusception (telescoping of the gut tube, cutting off its circulation). A panel of experts was convened by the US National Marine Fisheries Service on the topic of post-hooking mortality in January 2004. Although no hard data exist, based on the panel's input the agency prepared draft criteria that indicate the relative degree of impact on survival as a function of hook location and amount of gear remaining at release. Gut hooking, releasing entangled turtles, and resuscitation of drowned turtles are associated with the highest mortality rates. These criteria are being used by the agency to evaluate the impact of hook-and-line fishing activities on sea turtle survival (Epperly and Boggs 2004).

Circle hooks can reduce the mortality associated with fishing interactions for both fish and sea turtles. In a review of studies evaluating fish mortality associated with circle hooks compared with other types of hooks, Cooke and Suski (2004) concluded that overall the mortality rates were consistently lower for circle hooks than for J hooks. They found that circle hooks were more frequently hooked in the jaw and less frequently hooked in the gut. We found that also to be the case for swordfish, tuna, and blue shark caught with circle hooks on pelagic longlines. In addition, we found that not only can 18/0 circle hooks and mackerel bait significantly reduce both loggerhead and leatherback catch rates, but also significantly reduce the rate of gut hooking by loggerhead turtles. Because circle hooks are more likely to lodge in the jaw of a loggerhead rather than in the gut, hooks and line can be removed more easily. Dehookers and line cutters were used successfully by fishers to remove line and hooks from the turtles, including the leatherbacks, which most often were hooked externally and rarely were boated. The observed reduction in leatherback interactions with mackerel bait is believed to be the result of the fish bait masking the hook point.

In virtually all cases, loggerhead turtle interaction with pelagic longline gear appears to be a result of feeding behavior resulting in the apprehension and (or) ingestion of the bait, and data indicate that the interaction occurs primarily during daylight hours. The behavior leading to leatherback interactions with pelagic longline gear is not so apparent. While the majority of leatherback captures results from foul hooking, mostly in the shoulder, armpit, and front flipper area, some do ingest the bait. It is not known whether the interaction is a result of attraction to (*i*) bait upon which they are attempting to feed, (*ii*) light sticks used on the branchlines (light trapping or simple phototaxis), (*iii*) mainline, floats, buoys, branchlines, or hardware — structures in an otherwise featureless environment, or (*iv*) their mainstay prey, jellyfish, impinged upon the gear. Unlike loggerhead

Table 6. Odds ratio estimates from the models for blue sharks (*Prionace glauca*).

Effect	Odds ratio	95% Wald confidence limits		*p*
Treatment C_1S (0° offset 18/0 circle hook with squid bait)				
Hook type	1.081	1.021	1.144	0.0073
Sea surface temp.	0.886	0.877	0.895	<0.0001
Total soak time	1	0.999	1.000	0.0018
Daylight soak time	1.005	1.005	1.006	<0.0001
Treatment C_2S (10° offset 18/0 circle hook with squid bait)				
Hook type	1.094	1.031	1.162	0.003
Sea surface temp.	0.903	0.892	0.913	<0.0001
Total soak time	0.999	0.998	0.999	<0.0001
Daylight soak time	1.005	1.004	1.005	<0.0001
Treatment JM (25° offset J hooks with mackerel bait)				
Hook type	0.601	0.566	0.639	<0.0001
Sea surface temp	0.9	0.891	0.909	<0.0001
Total soak time	0.999	0.999	0.999	<0.0001
Daylight soak time	1.005	1.004	1.005	<0.0001
Treatment C_2M (10° offset 18/0 circle hooks with mackerel bait)				
Hook type	0.691	0.652	0.733	<0.0001
Sea surface temp.	0.889	0.880	0.897	<0.0001
Total soak time	0.999	0.999	0.999	<0.0001
Daylight soak time	1.005	1.004	1.005	<0.0001

Note: Sea surface temperature data were modeled in degrees Fahrenheit; soak times were were modeled in minutes.

turtles, leatherbacks do not have the ability to maneuver backwards (Davenport 1987; J. Wyneken, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431-0991, USA, personal communication) away from the lines and hooks and thus could become foul hooked even if attempting to ingest the bait. Research is needed to determine the nature of leatherback interactions to facilitate the development of more effective mitigation measures. Because leatherbacks over a large size range were foul hooked, these experimental results are applicable to leatherback turtles in other geographic areas. Furthermore, it is likely that the use of smaller circle hooks, with smaller gaps between the barb and shank, will be at least as effective in reducing foul hooking as the 18/0 circle hook tested. For loggerheads, however, these experimental results are applicable only for the sizes we encountered in the NED and for the sizes of the hooks we compared. There is evidence that the ability of a loggerhead to ingest a hook is a function of both the hook size and the animal's size (e.g., mouth gape) (Watson et al. 2003; S. Epperly, unpublished data). Bolten et al. (2002) found that although smaller circle hooks (16/0) significantly decreased the proportion of swallowed hooks by loggerheads of a size range comparable to the animals in the NED, when compared with 9/0 J hooks they did not reduce the rate of turtle interaction. Similarly, an 18/0 circle hook may not reduce the catch rates of a larger size class of loggerheads hypothetically found in other areas. Thus, we urge caution in extending these conclusions to geographic areas where loggerhead turtle size distributions may vary from those encountered during the experiments described herein.

The effect of sea surface temperature on turtle catch rates and swordfish catch rates with mackerel bait suggests that fishing cooler water (using real-time sea surface imaging technology) could reduce turtle interactions while sustaining swordfish catch. Fishing cooler water also would reduce the bycatch of blue shark, but it would negatively impact bigeye tuna catch.

Table 7. Hooks removed from loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles.

	Hook removed				
Hook Location	No	Yes	Unknown	NA*	Total
Loggerhead					
Swallowed	51	7	0	0	58
Mouth	1	30	0	0	31
External	0	2	0	0	2
Not known if hooked	0	0	0	1	1
Not hooked	0	0	0	4	4
Total	52	40	0	4	96
Leatherback					
Swallowed	0	0	0	0	0
Mouth	2	6	0	0	8
External	61	53	1	0	115
Not known if hooked	0	2	4	0	6
Not hooked	0	0	0	18	18
Unknown	1	0	0	0	1
Total	64	61	5	18	148

*Not applicable.

Previous studies have indicated a small degree of offset (≤4°) does not increase the rate of gut hooking, but an offset of 15° or larger does result in gut hooking comparable to that of a J hook (Malchoff et al. 2002; Prince et al. 2002;

Skomal et al. 2002); hook size may be a factor in the effect of offset. Our experimental design did not directly compare the two circle hooks, but rather each was compared with the J hooks. However, we found no significant differences in sea turtle and bigeye tuna catch rates of 10° offset and 0° offset 18/0 circle hooks baited with squid, but the two hooks were significantly different for swordfish and blue shark and did result in significantly more gut hooking in those two species. There were insufficient data to compare hooking locations in sea turtles as a function of offset. However, Canadian observer data (Javitech 2002) and experiments in the Azores (Bolten et al. 2002) do not indicate that 10° offset 16/0 circle hooks result in greater gut hooking of loggerhead turtles than 0° offset 16/0 hooks. For turtle species, swordfish, bigeye tuna, and blue sharks, the catch rates and proportion of gut hooking with the circle hooks were significantly different from those with J hooks. More research is needed to determine the effect on bycatch and target species of offset for different sizes of circle hooks.

The 18/0 circle hooks maintained catch efficiency for bigeye tuna when baited with squid and for swordfish when baited with mackerel. Circle hooks also significantly reduced gut hooking in these two species as well as in blue shark; presumably post-hooking survival of animals discarded also was increased. Circle hooks retained more sharks, but may not actually have caught more sharks than J hooks. The results presented on blue shark catch are likely confounded because sharks that are gut hooked are more likely to bite off monofilament leaders and thus escape detection at haulback. The benefit of using circle hooks for the target species is that undersized fish to be discarded likely have a higher probability of surviving the interaction, and those retained are more likely to be alive on the line at haulback, resulting in a higher quality product for the market.

Because sea turtles are migratory, cross international boundaries, and often are outside the boundaries of any national jurisdiction, successful methods adopted by one nation's vessels may not be sufficient to ensure species recovery, unless they also are adopted by the vessels of other nations. The sea turtle mitigation techniques described in this paper can be exported to other fisheries and countries for evaluation, but more research is needed on pelagic longline gear modifications to develop effective bycatch mitigation techniques for longline fisheries worldwide. Circle hooks (18/0) and mackerel bait were found to be highly effective in reducing turtle interactions with pelagic longline gear and were effective in maintaining the primary target catch in the Western Atlantic swordfish fishery, but may not be as effective in other areas and for other target species or size classes of swordfish or loggerheads. The majority of worldwide pelagic longline fishing effort targets tuna, and research is needed to determine if large circle hooks are effective in catching species other than bigeye tuna. Mackerel bait also was found to be effective in reducing sea turtle interactions compared with squid bait, but mackerel bait was ineffective in catching bigeye tuna. Most tuna fisheries use fish species for bait that are smaller than the mackerel evaluated in this study. Observer data from the Gulf of Mexico indicate that loggerhead interactions in a fishery predominately targeting yellowfin tuna may be reduced by using small fish bait (sardines and herring) in combination with 16/0 circle hooks (Garrison 2003). More research is needed on the effect of hook size and hook design to maximize hook efficiency in reducing sea turtle interactions and maintaining target catch.

As the world population continues to grow and the demand for fisheries resources increases, bycatch has become a serious concern in the effort to wisely manage the world's fisheries resources (Alverson et al. 1994). The development of selective fishing technologies and strategies can be effective in reducing the ecological impact of fishing practices by reducing bycatch and discards. To be effective, these measures must be efficient in harvesting target species, or they will likely be resisted by users (Witherall 2004). We have demonstrated that selective fishing techniques can be developed that are capable of reducing the unintended ecological impact of pelagic longline fishing while maintaining effective harvesting efficiency. We have outlined an experimental design that is effective in evaluating gear modification treatment effects on bycatch and target species catch. The results of this study indicate that it is possible to mitigate turtle interactions with the longline fishery by manipulating hook style and bait type while still maintaining catch of targeted fish species. Furthermore, implementation of the techniques developed as a result of our research made it possible to reopen both the Hawaii-based pelagic longline fishery and the NED to United States longline fishermen, effective 3 May 2004 and 6 July 2004, respectively (US Department of Commerce 2004*a*, 2004*b*). We encourage international evaluation of the techniques described here, as well as research to develop more effective and selective fishing technologies.

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Appendix A

Power analysis

The null hypothesis for the experiment was constructed so that the burden of proof is on the treatment to be proven; that is, we initially assumed that the treatment is not effective unless there was enough (statistical) evidence otherwise for its effectiveness. The factors affecting the required level of effort were the actual sea turtle catch rates and variability, the effectiveness of a measure being tested (i.e., the difference in catch rate between the experimental and control treatments), and acceptable risk levels for type I and type II errors. We projected the expected sea turtle catch rates based on the average catch rate observed in the Grand Banks fishery over 1991–1999 (Yeung 2001). For the expected effectiveness of the treatments, we looked at 50% and 25% bycatch reduction. We chose 25% as the minimum accept-

able reduction rate useful to sea turtle management and conservation. The detection of reduction rates below 25% would also require a very large increase in the effort. We set α (probability of rejecting true null hypothesis) and β (probability of accepting false null hypothesis) levels at 10% and 20%, respectively, which are typical levels of statistical risk for this type of gear evaluation experiment. The number of hooks required to detect a 25% and 50% reduction in loggerhead catch per unit effort (CPUE) was 54 054 and 9012 hooks per treatment, respectively. Comparative efforts for leatherback turtles were 163 548 and 26 828 hooks per treatment, respectively. The number of hooks fished in our experiment was at least 70 700 per treatment, giving us the power of a least 80% to detect a 25% reduction in loggerhead catch and 50% reduction in leatherback catch.