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EVALUATION OF HOOK AND BAIT TYPE ON THE CATCH RATES IN THE WESTERN NORTH ATLANTIC OCEAN PELAGIC LONGLINE FISHERY

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ABSTRACT

Research was conducted in 2002 and 2003 by NOAA's National Marine Fisheries Service, Southeast Fisheries Science Center, to investigate changes in hook design and bait type to reduce the bycatch of sea turtles on pelagic longlines in the western North Atlantic Ocean. The effectiveness of 18/0–20/0 circle hooks and 10/0 Japanese tuna hooks with squid (*Illex* spp.) and mackerel bait (*Scomber scombrus* Linnaeus, 1758) was evaluated against the industry standard 9/0 J-hooks with squid bait with respect to reducing sea turtle and shark interactions while maintaining swordfish (*Xiphias gladius* Linnaeus, 1758) and tuna (*Thunnus* spp.) catch rates. In total, 973,734 hooks were deployed during the study. Individually, circle hooks and mackerel bait significantly reduced both loggerhead [*Caretta caretta* (Linnaeus, 1758)] and leatherback [*Dermochelys coriacea* (Vandelli, 1761)] sea turtle bycatch. The combination of 18/0 circle hooks with mackerel bait was even more effective for loggerhead sea turtles and had a significant increase in swordfish catch by weight. The combination 18/0 circle hooks with squid bait resulted in a significant decrease in the swordfish catch and a significant increase in the catch rate of blue shark [*Prionace glauca* (Linnaeus, 1758)], bluefin tuna [*Thunnus thynnus* (Linnaeus, 1758)], and albacore tuna [*Thunnus alalunga* (Bonnaterre, 1788)]. With all hook types, mackerel bait resulted in a significant decrease in blue shark, bigeye tuna [*Thunnus obesus* (Lowe, 1839)], and albacore tuna, but significantly increased the catch of porbeagle [*Lamna nasus* (Bonnaterre, 1788)] and shortfin mako (*Isurus oxyrinchus* Rafinesque, 1810).

Pelagic longlines are the primary method of commercial harvest of large pelagic fishes worldwide (Watson and Kerstter 2006). Target species for this fishing method include swordfish (*Xiphias gladius,* see Table 1 for species authorities) and tunas (*Thunnus* spp.). However, catches also consist of non-target species (bycatch) that are discarded because they have no commercial value or due to regulatory measures. In the US, protected species include sea turtles, seabirds, marine mammals, and some shark and istiphorid billfish species. The reduction in interaction rate and discard mortality of bycatch has become a significant issue in fisheries management, with extensive research aimed to increase selectively of fishing gear to minimize waste due to discard (Hall et al. 2000, Moore et al. 2009).

The bycatch of loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles in pelagic longline fisheries has resulted in US management actions designed to reduce the impact of the pelagic longline fisheries on sea turtle populations in both the Pacific Ocean and Atlantic Ocean. Prime fishing grounds, including international waters of both the Pacific and Atlantic, were closed to US fishermen in an attempt to reduce incidental fishing mortality of sea turtles in the longline fishery

(US Department of Commerce 1999, 2000). The Northeast Distant (NED) statistical reporting area in the western North Atlantic, including the productive Grand Banks, was closed to the US 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, 2001a,b).

In developing an alternative mitigation measure, National Marine Fisheries Service (NMFS), in cooperation with the Blue Waters Fishermen's Association, conducted bycatch mitigation research from 2001 to 2003 on the Grand Banks, western Atlantic Ocean. The research aimed to determine if the use of circle hooks with mackerel bait (*Scomber scombrus* Linnaeus, 1758) could reduce interactions and post release mortality of sea turtles in the swordfish fishery. The predominant hook type used historically in the US western Atlantic pelagic longline fishery for swordfish was the offset 9/0 J-hook and the predominant bait was squid (*Illex* spp., Hoey and Moore 1999). Only a portion of the 2002 data was published (Watson et al. 2005), yet these data demonstrated that individually, 18/0 circle hooks and mackerel bait significantly reduced both loggerhead and leatherback sea turtle bycatch. The combination of circle hooks with mackerel bait was even more effective for loggerhead turtles and had no negative effect on swordfish catch. Circle hooks also significantly reduced the rate of hook ingestion by the loggerheads, potentially reducing post release mortality (Ryder et al. 2006).

The 2002 results, combined with the unpublished 2003 results, culminated in the mandatory requirement of US pelagic longline fishers in both the Atlantic fishery and in the Hawaii-based shallow set longline fishery to use circle hooks. The implementation of the modifications in fishing methods, in conjunction with tools and techniques developed to remove hooks and line from the turtles made it possible to reopen both the Hawaii-based pelagic longline fishery and the NED to US longline fishers, effective 3 May, 2004, and 6 July, 2004, respectively (US Department of Commerce 2004a,b). The present analyses combine the 2002 and 2003 trials, adding to the research presented in Watson et al. (2005) by substantially increasing the sample size of the evaluations of 18/0 circle hooks and increasing the list of species evaluated by including two additional tuna and two additional shark species. The present study also expands on the previous work by evaluating two additional hook and bait combinations, 20/0 circle hooks and 10/0 Japanese tuna hooks with mackerel bait.

Methods

Experimental Design

The experimental design followed the methods described in Watson et al. (2005). The selection of treatments was made jointly between industry representatives and researchers. We evaluated the effectiveness of circle hooks (C) vs J-hooks (J) and mackerel bait vs squid bait for reducing the sea turtle interaction rate and injury associated with pelagic longline gear. The selection of 18/0 and 20/0 circle hooks was based on research conducted by Bolten et al. (2002), which showed that while 16/0 circle hooks reduce the rate of deep ingestion by loggerhead sea turtles as compared to J-hooks, they are not large enough to reduce the rate of interaction. The choice of mackerel bait was due to anecdotal information provided by fishers suggesting that mackerel bait may result in a lower catch rate of loggerhead sea turtles. The control treatment was the industry standard 10°–30° offset J-hooks with squid bait (JS). Offset hooks are hooks with the point bent sideways (usually 10°–30°) in relation to the shank.

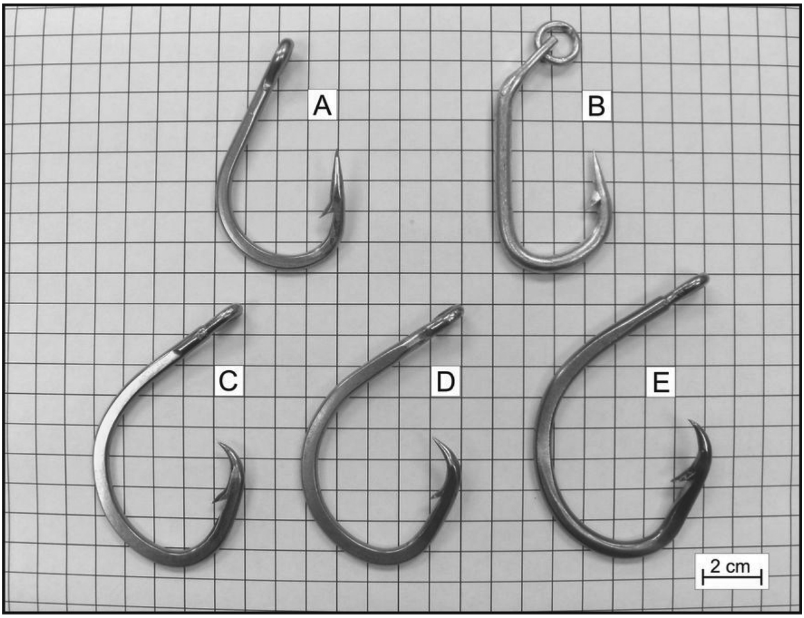

Figure 1. Hooks used during the 2002 and 2003 pelagic longline experiments in the western North Atlantic (NED): (A) LP-SW 10° offset J-hook, (B) 0° offset 10/0 Japanese tuna (J-tuna) hook, (C) 0° offset 18/0 circle hook, (D) 10° offset 18/0 circle hook, (E) 10° offset 20/0 circle hook.

The treatments evaluated were: (1) Industry Standard: 10°–30° offset J-hooks with squid bait (JS), (2) 0° offset 18/0 circle hooks with squid bait (C_1S), (3) 10° offset 18/0 circle hooks with squid bait (C_2S), (4) 10° offset 18/0 circle hooks with mackerel bait (C_2M). (5) 10° offset 20/0 circle hooks with mackerel bait (C_3M), (6) 10°–30° offset 9/0 J-hooks with mackerel bait (JM), and (7) 0° offset 10/0 Japanese tuna hook (J-tuna) with mackerel bait (JTM).

Only offset circle hooks were evaluated with mackerel bait because it is purportedly difficult to place mackerel on 0° offset 18/0 circle hooks. Circle hooks were from a single manufacturer, Lindgren-Pitman, Inc. (LP; Pompano Beach, Florida). The 10º offset and 0º offset 18/0 hooks were #LP-CIR-HOOK-18-O and #LP-CIR-HOOK-18-S, respectively. The 20/0 circle hooks were #LP-CIR-HK-20-0-10. The J-tuna hooks were Mustad #9202SR (O. Mustad & Son, A.S., Gjövik, Norway; Fig. 1).

During each set, two hook types were alternated on each longline section (length of mainline between highflyer buoys) along the entire set. Experimental configurations deployed in 2002 were JS/C_1S, JS/C_2S, and JM/C_2M. Configurations deployed in 2003 were JS/C_1S, C_2M/C_3M, and C_2M/JTM. The hook types added in 2003 (20/0 circle hooks and J-tuna hooks) were tested only with mackerel bait due to favorable results observed with mackerel in 2002 for both target catch and sea turtle mitigation (Watson et al. 2005). For each experimental treatment, the catch rate with JS for corresponding year(s) was used for the comparison, e.g., the catch rate of JS in 2003 was used in the comparison for C_3M.

For each year, vessels alternated among the three experimental set configurations. Only one bait type was used within a set to avoid possible interaction effects of bait types. On every set, vessels deployed the gear with three or five hooks fished between each set of floats: one placed directly adjacent to each float, and the others placed between the floats at an equal distance from each other. Bait size and light sticks were standardized among the vessels to reduce variability. Bait used was 150–300 g squid bait or 200–500 g mackerel bait. Green light sticks and leaded swivels were used on every leader, and placement was consistent. Hook spacing, hooks between floats, branchline length and size, mainline and leader color, and baiting technique were consistent within a trip. Control hooks were Mustad 9/0 #7698 RD, Mustad 9/0 #76801, Eagle Claw 9/0 #9016 (Eagle Claw Fishing Tackle Co., Denver, Colorado), or LP-SW 9/0. The LP-SW 9/0 (10° offset) was the predominant J-hook used. 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 US fishing vessels in 2000 (Hoey and Moore 1999, Beerkircher et al. 2002).

Data Collection

All vessels participating in the experiment carried observers, and both the observers and the captains were well versed on the experimental design. Observers collected fishery data as described by the Southeast Fisheries Science Center Pelagic Longline Observer Program (Beerkircher et al. 2002), with minor modifications to accommodate the experiment. The time and location of each section of gear was recorded as it was deployed and retrieved, as well as the sea surface temperature at the time of deployment. The section number, treatment (hook type and style), time on deck, animal condition (alive, dead, or damaged), and species were recorded for each animal captured. If boated, length was measured in centimeters. Length was estimated for animals not boated. A carcass tag applied to each fish was used to match the dressed weight (eviscerated carcass with head and fins removed) of the fish during unloading at the dock to the particular data collected on that individual 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 type was recorded. 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. When possible, sea turtles (loggerheads) were boated with a large dip net. Boated turtles were measured to the nearest millimeter and tagged. Observers attempted to remove all gear immediately. 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. The protocols for collecting sea turtle capture data and gear removal are available online at http://www.sefsc.noaa.gov/seaturtlefisheriesobservers.jsp.

Statistical Methods

The relationship between the catch rate (or catch probability) and the explanatory variables (hook type, sea surface temperature, daylight soak time, total soak time, and year) was investigated using generalized linear models (Draper and Smith 1998, Hosmer and Lemeshow 2000, Watson et al. 2005, Agresti 2007). Specifically, logistic regression analysis with maximum likelihood estimation procedure for binary response count data was used for non-target species and traditional least squares regression analysis for continuous response weight data was used for swordfish and bigeye tuna (*Thunnus obesus*) 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. The effect of hook depth was not examined because swordfishers set hooks at approximately the same depth. Set was the experimental unit in the models. 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., pounds dressed weight and degrees Fahrenheit sea surface temperature).

Because the probability of a sea 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 treatment. Approximation of relative risk for other factors also utilized odds ratios 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 mean 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 sea turtle capture for control and experimental hooks) is a natural scale for the logistic model, 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 variables. All statistical analyses were performed in SAS Statistical Software (SAS, version 9.1, SAS Inst., Inc., Cary, NC). Statistical significance was declared at $P < 0.05$.

Results

From July 2002 to November 2003, 13 commercial longline vessels made 999 research sets in the NED, fishing a total of 973,734 hooks. The number of hooks set per hook and bait combination are as follows: JS = 255,298; C_1S = 184,147; C_2S = 71,150; C_2M = 231,570; C_3M = 137,789; JM = 70,990; JTM = 22,790. The treatments of JS, C_1S, and C_2M were tested in both 2002 and 2003, with the hooks set in 2003 accounting for 44%, 61%, and 69% of the total hooks set by treatment, respectively. Vessels fished a mean of 975 hooks per set; the minimum number of hooks fished in a set was 80 hooks, and the maximum was 1610 hooks. The mean number of sections per set was eight and the range was 1–11. 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. 2, 3). The combined length of float lines and branchlines was between 9.1 and 29.3 m, which represent the approximate depth of the hooks, excluding curvature of mainline. Mean soak times ranged from 506 to 2805 min, with a mean of 789 min and standard deviation of 117 min, while temperature ranged from 12 to 24 °C, with a mean of 17 °C and standard deviation of 1.6 °C. The vessels caught 49 animal taxa. Twelve taxa accounted for >99% of all animals captured (Table 1). We constructed models for taxa representing at least 1% of the catch. We also analyzed

Table 1. The most frequent taxa observed during the 2002–2003 pelagic longline experiments on the Grand Banks.

Species and authority	Common name	Frequency	Percent
Prionace glauca (Linnaeus, 1758)	Blue shark	24,949	49.4
Xiphias gladius Linnaeus, 1758	Swordfish	19,366	38.3
Thunnus obesus (Lowe, 1839)	Bigeye tuna	1,620	3.2
Lamna nasus (Bonnaterre, 1788)	Porbeagle	1,311	2.6
Isurus oxyrinchus Rafinesque, 1810	Shortfin mako shark	700	1.4
Thunnus alalunga (Bonnaterre, 1788)	Albacore tuna	558	1.1
Alepisaurus spp.	Lancetfishes	346	0.7
Thunnus thynnus (Linnaeus, 1758)	Bluefin tuna	313	0.6
Rajiformes	Rays, skates	280	0.6
Coryphaena spp.	Dolphinfishes	275	0.6
Dermochelys coriacea (Vandelli, 1761)	Leatherback sea turtle	228	0.5
Caretta caretta (Linnaeus, 1758)	Loggerhead sea turtle	171	0.3

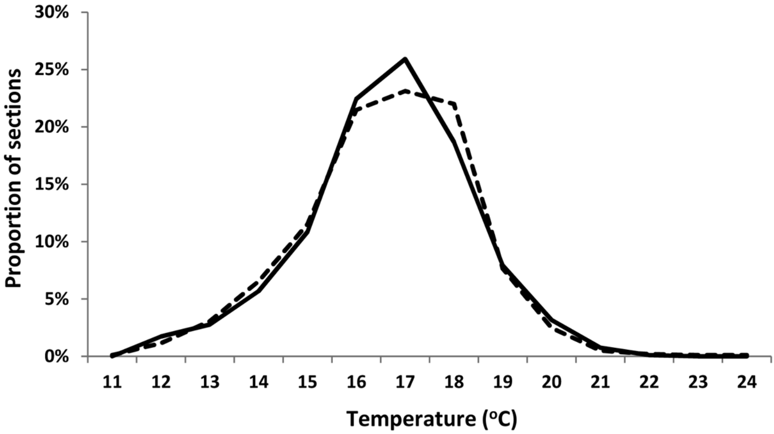

Figure 2. Sea surface temperature distribution (mean section temperature) by bait type. Solid line represents temperatures at which mackerel (*Scomber scombrus*) bait were fished; dashed line represents temperatures at which squid (*Illex* spp.) bait were fished.

data for bluefin tuna and the two sea turtle species because they either were protected species (sea turtles) or were being considered for listing as a protected species (bluefin: US Department of Commerce 2011) under the US Endangered Species Act. Tables providing the odds ratio or parameter estimates, with the resulting CIs and P values from the models can be found in the Online Supplementary Tables for this article.

The target species, swordfish and bigeye tuna, along with blue shark, were the species most often caught. The vessels kept for sale 16,309 swordfish (total dressed weight of 828.7 t) and 1446 bigeye tuna (total dressed weight of 48.9 t). Blue shark was the species most frequently captured, but few (n = 7, total dressed weight = 0.2 t) were kept. During the course of the experiment, 228 loggerhead and 171 leatherback sea turtles were captured and released alive. The vessels also captured 14 seabirds and 15 marine mammals: five unidentified seabirds (one estimated at 40 cm in length), five Greater Shearwaters [*Puffinus gravis* (O'Reilly, 1818)], two Shearwaters (*Puffinus* spp.), one Northern Gannet [*Morus bassanus* (Linnaeus, 1758)], one Laughing Gull [*Leucophaeus atricilla* (Linnaeus, 1758)], eight Risso's dolphins [*Grampus griseus* (Cuvier, 1812)], two oceanic dolphins (*Stenella* spp.), one common dolphin (*Delphinus delphis* Linnaeus, 1758), one striped dolphin [*Stenella coeruleoalba* (Meyen, 1853)], one pilot whale (*Globicephala* spp.), one baleen whale (Mysticeti), and one unidentified marine mammal. All mammals except one Risso's dolphin were released alive, as were the Northern Gannet, one Greater Shearwater, and three unidentified seabirds.

Treatment Effects

Loggerhead Sea Turtles.—Loggerheads ranged from 35 to 76 cm standard straight line carapace length (SCLstd) and averaged 60.9 cm. The highest reduction rates for loggerhead sea 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. The combination reduced loggerhead catch by 88% (CI = 77%–94%, $P < 0.0001$). The second highest reduction was achieved with 20/0 circle hooks with mackerel bait (87%, CI = 68%–95%, $P < 0.0001$). Circle hooks with squid bait reduced loggerhead catch by 74% (CI = 58%–84%, $P < 0.0001$) for 0° offset hooks

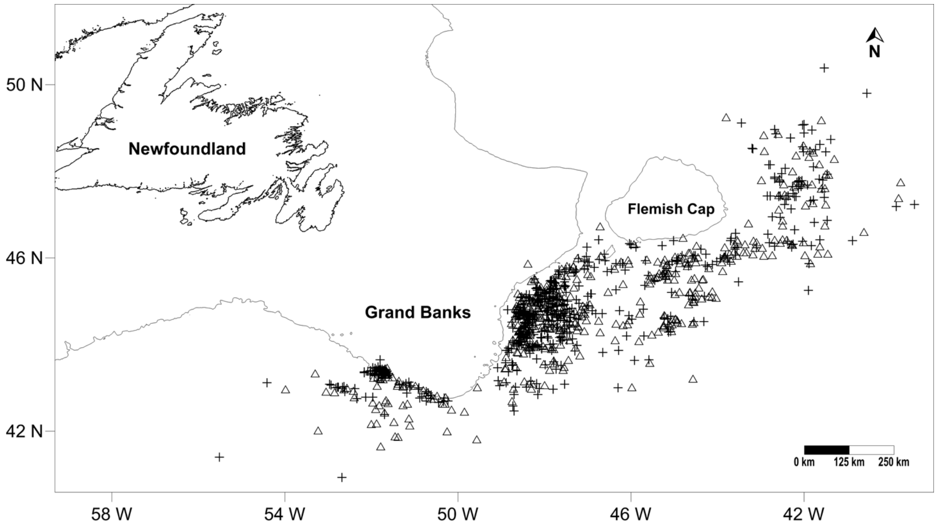

Figure 3. Geographical effort distribution by bait type. Triangles represent sets using mackerel (*Scomber scombrus*) bait; crosses represent sets using squid (*Illex* spp.) bait.

and 85% (CI = 65%–94%, $P < 0.0001$) with 10° offset hooks (Fig. 4A). Mackerel bait on J-hooks reduced the catch rate by 75% (CI = 47%–88%, $P < 0.0001$). The odds ratio ranged from 0.12 to 0.26 in these models, suggesting the loggerhead sea turtle catch on the industry standard hook and bait was between 3.9 and 8.3 times (increase of 290%–730%) that of the experimental hooks and bait. A reduction was observed with J-tuna hooks (JTM), but the reduction was not significant ($P = 0.957$).

The sea surface temperature effect for loggerhead sea turtles was highly significant in all of the models ($P < 0.0001$). The loggerhead sea turtle catch rate increased by a multiplicative factor of 25%–67% with each 0.6 °C increase in sea surface temperature (note: extrapolations of effects of sea surface temperature outside the range observed are not appropriate). The effect of total soak time on loggerhead sea turtle catch was highly significant ($P \leq 0.0002$) as well, suggesting an increase in the loggerhead sea turtle catch rate by a multiplicative factor of 0.7%–1.3% with each unit increase (min) in total soak time. A negative effect was observed for daylight soak time which was highly significant for all models except C_2S ($P = 0.826$), indicating a decrease in catch rate by a factor of 0.1%–1.9% with each minute increase in daylight soak time. We suspect that there was a confounding interaction between total soak time and daylight soak time. Swordfish sets were made at sunset and retrieved early in the morning, thus any increase in total soak time also increased in daylight soak time. The year effect was significant for the C_1S (odds ratio 2.209, $P = 0.001$), indicating that a higher catch rate of loggerhead sea turtles occured in 2003.

Leatherback Sea Turtles.—The estimated carapace lengths of leatherbacks ranged from 100 to 210 cm, with a mode of 150 cm. A significant reduction in the leatherback sea turtle catch rate was achieved by all of the treatment combinations evaluated except J-tuna hooks (JTM). Circle hooks with squid bait reduced the catch rate by 76% (CI = 57%–86%, $P < 0.0001$) with 0° offset hooks and 49% (CI = 9%–71%, $P < 0.022$) for 10° offset hooks. Mackerel bait on J-hooks reduced leatherback catch by 66% (CI = 36%–82%, $P < 0.0001$). Circle hooks with mackerel bait reduced leatherback catch by

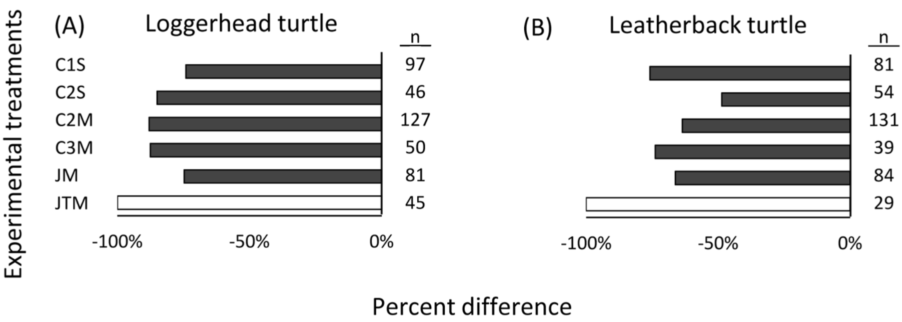

Figure 4. Percent difference in (A) loggerhead sea turtle and (B) leatherback sea turtle catch rates between 9/0 J-hook with squid bait (control) and 0° offset 18/0 circle hooks with squid bait (C_1S), 10° offset 18/0 circle hooks with squid bait (C_2S), 10° offset 18/0 circle hooks with mackerel bait (C_2M), 10° offset 20/0 circle hooks with mackerel bait (C_3M), 10°–30° offset 9/0 J-hooks with mackerel bait (JM), and 0° offset 10/0 Japanese tuna hook (J-tuna) with mackerel bait (JTM), estimated from logistic regression models. Solid bars denote a significant difference at $\alpha < 0.05$.

63% (CI = 44%–76%, $P < 0.0001$) for 18/0 hooks and 74% (CI = 46%–87%, $P = 0.0003$) with 20/0 hooks (Fig. 4B). The leatherback sea turtle catch rate on the control hook and bait was 2.0–4.6 times (increase of 100%–360%) that of the experimental hooks and bait (the odds ratios ranged from 0.24 to 0.51).

The sea surface temperature effect for leatherback sea turtles was highly significant in all of the models ($P \leq 0.005$). The leatherback catch rate increased by a multiplicative factor of 16%–31% with each 0.6 °C increase in sea surface temperature. The total and daylight soak time effect was inconclusive for leatherbacks with only daylight soak time for JTM being significant (0.7% increase, $P = 0.041$). The C_2S and C_2M models revealed a significantly lower catch rate of leatherback sea turtles in 2003 ($P \leq 0.021$).

Swordfish.—Swordfish is the primary target species in the NED fishery studied. Swordfish caught averaged 163 cm in lower jaw curved fork length (range 20–290 cm), and the mean weight of swordfish retained was 50.9 kg (range 10.9–251.8 kg). Swordfish catch rate increased by 17% (CI = 6%–28%, $P = 0.003$) on 18/0 circle hooks with mackerel bait and 59% (CI = 41%–76%, $P < 0.0001$) by J-hooks with mackerel bait (Fig. 5). Both 0° offset and 10° offset 18/0 circle hooks with squid bait significantly reduced swordfish catch by 31% (CI = 21%–41%, $P < 0.0001$) and 29% (CI = 13%–45%, $P = 0.0003$), respectively. A reduction of 31% (CI = 3%–59%, $P = 0.028$) was also observed with the J-tuna hook with mackerel bait.

Sea surface temperature did not significantly affect swordfish catch in any treatment combination ($P \geq 0.13$). The effect of total soak time on swordfish catch rate was inconsistent among the models. Swordfish catch rate increased significantly with increased total soak time for 10° offset 18/0 circle hooks with squid bait (C_2S, $P = 0.036$). However, the models for C_1S and JTM show an inverse effect ($P \leq 0.007$). The effect of daylight soak time was positive and significant for all models ($P \leq 0.001$). 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

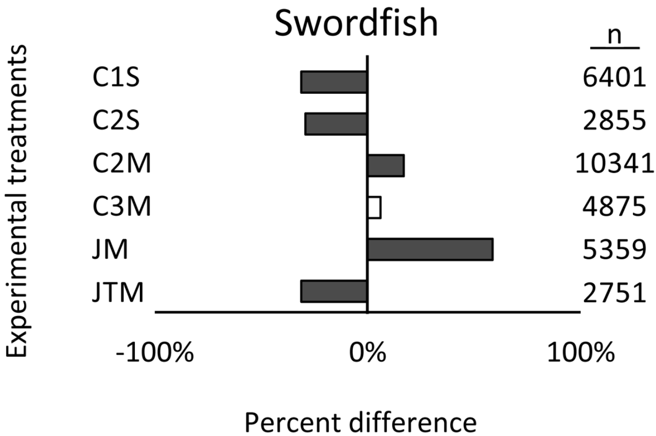

Figure 5. Percent difference in swordfish catch rates between 9/0 J-hook with squid bait (control) and 0° offset 18/0 circle hooks with squid bait (C_1S), 10° offset 18/0 circle hooks with squid bait (C_2S), 10° offset 18/0 circle hooks with mackerel bait (C_2M), 10° offset 20/0 circle hooks with mackerel bait (C_3M), 10°–30° offset 9/0 J-hooks with mackerel bait (JM), and 0° offset 10/0 Japanese tuna hook (J-tuna) with mackerel bait (JTM), estimated from traditional regression models. Solid bars denote a significant difference at $\alpha < 0.05$.

increased time required for handling and processing the catch. There was a significant year effect in the model for C_2M with a higher catch rate observed in 2002 ($P < 0.0001$).

Tunas.—Bigeye tuna is a secondary target catch in the fishery and is retained for sale. Bigeye tuna caught averaged 127 cm upper jaw fork length (range 60–199 cm) and the mean weight of retained fish was 33.7 kg (range 10.9–87.7 kg). Mackerel bait significantly reduced the catch rate of bigeye tuna (82%–94%) for all hook types evaluated ($P \leq 0.008$, Fig. 6A). The initial model for the J-tuna hook with mackerel bait was not significant and moreover produced a negative parameter estimate for catch per unit hook with the J-tuna hook. As a result, we reverted to a simpler linear model with only the term of hook type, which was significant and it had a more realistic parameter estimates.

Bluefin tuna caught averaged 188 cm upper jaw fork length (range 62–282 cm) and the mean weight of retained fish was 163.6 kg (range 40–321.8 kg). Bluefin catch rate was increased for all hook and bait combinations with the exception of J-hooks with mackerel bait. Significant increases of 189% and 46% were observed for 10° offset 18/0 circle hooks with both squid and mackerel bait (C_2S and C_2M) respectively ($P \leq 0.039$, Fig. 6B). The increases in catch rate for 0° offset 18/0 circle hooks (44%), 10° offset 20/0 circle hooks (25%), and J-tuna hooks (24%) were not significant ($P \geq 0.060$).

Albacore tuna caught averaged 93 cm upper jaw fork length (range 47–117 cm) and the mean weight of retained fish was 13.4 kg (range 8.2–35 kg). Circle hooks baited with squid significantly increased the catch rate of albacore tuna on 0° offset (31%, CI = 6%–62%, $P = 0.014$) and 10° offset 18/0 circle hooks (78%, CI = 25%–152%, $P = 0.001$; Fig. 6C). Mackerel bait reduced the catch rate of albacore tuna on all hook types evaluated. The reduction was significant for all hook combinations except J-tuna hooks (range 85%–97%, $P < 0.0001$).

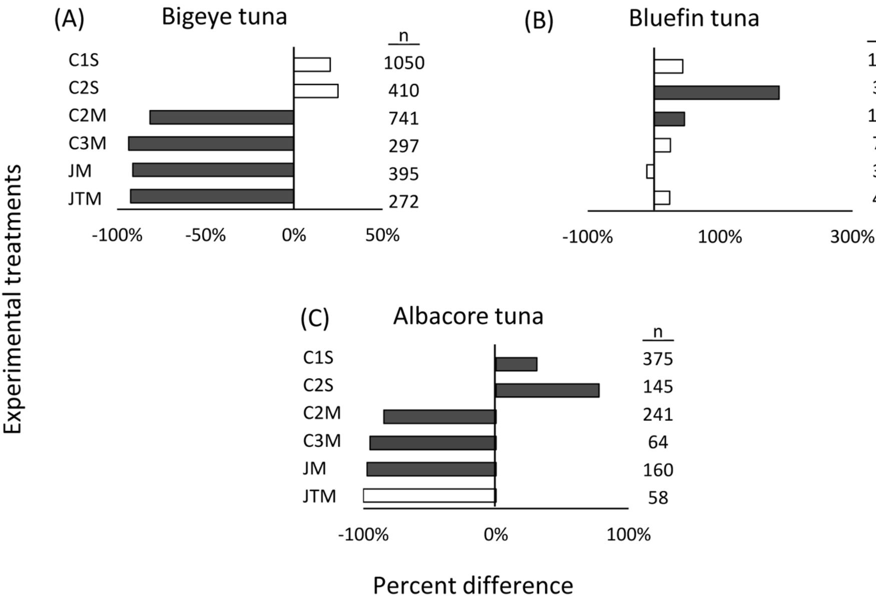

Figure 6. Percent difference in (A) bigeye tuna, (B) bluefin tuna, (C) and albacore tuna catch rates between 9/0 J-hook with squid bait (control) and 0° offset 18/0 circle hooks with squid bait (C_1S), 10° offset 18/0 circle hooks with squid bait (C_2S), 10° offset 18/0 circle hooks with mackerel bait (C_2M), 10° offset 20/0 circle hooks with mackerel bait (C_3M), 10°–30° offset 9/0 J-hooks with mackerel bait (JM), and 0° offset 10/0 Japanese tuna hook (J-tuna) with mackerel bait (JTM), estimated from traditional and logistic regression models. Solid bars denote a significant difference at $\alpha < 0.05$.

The sea surface temperature effect for the three tuna species was highly significant ($P \leq 0.007$) with the exception of model C_3M for bigeye tuna ($P = 0.835$). For the statistically significant models, catch rate for bigeye tuna increased by between 5 and 17.3 kg per 1000 hooks with each 0.6 °C increase in sea surface temperature, depending on the treatment comparison. Albacore increased by a multiplicative factor of 14%–19% with each 0.6 °C increase in sea surface temperature. Bluefin tuna catch rate decreased by a multiplicative factor of 14%–20%. The effect of total soak time was varied and inconclusive for all three tuna species (P values ranging from < 0.0001 to 0.400). The effect of daylight soak time on bluefin and albacore tuna catch was positive and significant ($P \leq 0.022$) for all treatment combinations except for the JM model with albacore ($P = 0.216$). The daylight soak time results were inconclusive for bigeye. A significant year effect was observed for bigeye and albacore tuna with higher catch rates occurring in 2002 ($P \leq 0.017$).

Sharks.—Blue shark is primarily a bycatch species in the NED fishery studied. The catch rate of blue shark was increased 4% (CI = 0%–8%, $P = 0.046$) by 0° offset circle hooks with squid bait and 8% (CI = 2%–15%, $P = 0.010$) by 10° offset circle hooks with squid bait. Mackerel bait significantly reduced the catch rate of blue shark, ranging from 30% to 44% ($P < 0.0001$) for all hook types evaluated (Fig. 7A). Mackerel bait significantly increased the catch rate of porbeagle (148%–374%, $P < 0.0001$) and shortfin mako shark (162%–329%, $P \leq 0.001$; Figs. 7B,C). The catch rate of neither

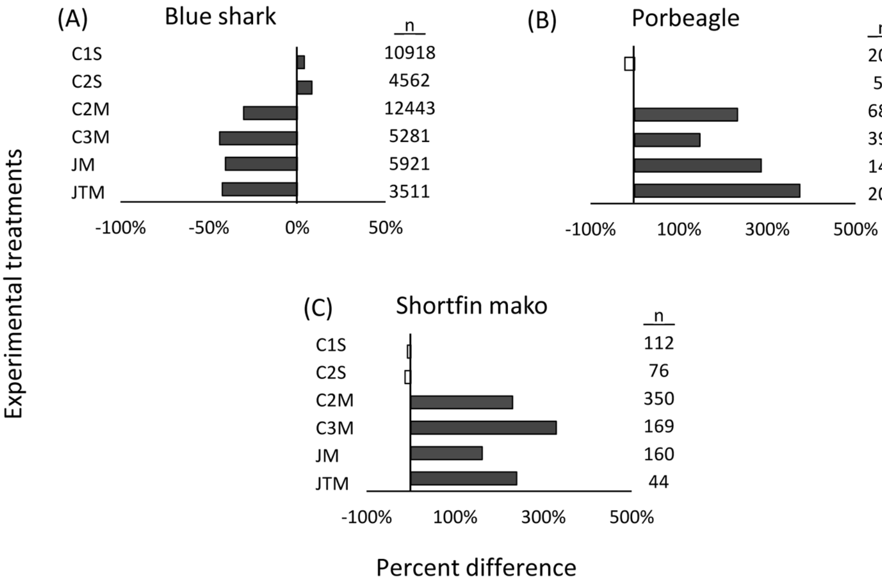

Figure 7. Percent difference in (A) blue shark, (B) porbeagle, and (C) shortfin mako catch rates between 9/0 J-hook with squid bait (control) and 0° offset 18/0 circle hooks with squid bait (C_1S), 10° offset 18/0 circle hooks with squid bait (C_2S), 10° offset 18/0 circle hooks with mackerel bait (C_2M), 10° offset 20/0 circle hooks with mackerel bait (C_3M), 10°–30° offset 9/0 J-hooks with mackerel bait (JM), and 0° offset 10/0 Japanese tuna hook (J-tuna) with mackerel bait (JTM), estimated from logistic regression models. Solid bars denote a significant difference at $\alpha < 0.05$.

porbeagle nor shortfin mako was significantly affected by circle hooks with squid bait ($P \geq 0.071$).

The sea surface temperature effect for blue shark and porbeagle was highly significant in all of the models ($P < 0.0001$). The blue shark catch rate decreased by a multiplicative factor of 4%–9% with 0.6 °C increase in sea surface temperature. Porbeagle catch rate decreased by a factor of 15%–28%. Shortfin mako exhibited a significant sea surface temperature response for all treatment combinations except for 10° offset 18/0 circle hooks with squid bait. For the models with a significant temperature effect, shortfin mako catch rate increased by a multiplicative factor of 18%–25% ($P \leq 0.0003$) with 0.6 °C increase in sea surface temperature. The total soak time and daylight soak time effect on blue shark and porbeagle catch rates was highly significant ($P < 0.0001$) for 11 of the 12 models, with the exception being the C_2S model for porbeagle ($P \geq 0.162$). The significant models were fairly consistent for total soak time effect, with a decrease in catch rate by a factor of 0.1%–0.4% for each minute increase in total soak time for blue shark and 0.5%–0.8% for porbeagle. The daylight soak time effect was positive with an increase in catch rate by 0.5%–0.8% per minute increase of daylight soak time for blue shark and 0.6%–0.9% for porbeagle. The total and daylight soak time effects for shortfin mako were varied (P values ranging from < 0.0001 to 0.750). A significant year effect was observed with for all three shark species with the highest catch rate of blue shark and shortfin mako occurring in 2002 ($P \leq 0.015$). The highest catch rate for porbeagle was observed in 2003 ($P \leq 0.006$).

Discussion

Pelagic longline gear is made up of four primary components: the mainline, the buoy/float lines, the branchlines, and hooks with bait, all of which are adaptable. Changes in materials or deployment strategies can alter the catch composition associated with the gear (Watson and Kerstetter 2006). For example, in the late 1970s longliners targeting bigeye tuna began shifting fishing practices by increasing the number of branchlines between floats which increased the depth range of the gear. The change resulted in an increase in the catch rate of bigeye tuna and a reduction in the catchability of some marlins and sailfish, *Istiophorus platypterus* (Shaw in Shaw and Nodder, 1792), (Serafy et al. 2004, Ward and Myers 2005).

In the present study, we explored a combination of hook and bait types as a means to reduce sea turtle mortality associated with pelagic longlines as well as examined the effect on the catch rate of target fish as well as shark species. Results presented here expand the Watson et al. (2005) study by substantially increasing the sample size of the previously reported treatments JS, C_1S, and C_2M; evaluating the additional treatments C_3M and JTM; and increasing the list of species evaluated by including two additional tuna and two additional shark species. Consistent with the previous analyses, results demonstrate that loggerhead and leatherback sea turtle interactions associated with the western Atlantic pelagic swordfish longline fishery can be significantly reduced by employing 18/0–20/0 circle hooks or by using mackerel bait in place of squid bait. Importantly, when the two treatments are used in combination, the resulting reduction in turtle interactions, ≥87% for loggerheads and ≥63% for leatherbacks, can be obtained without negatively impacting swordfish catch on the Grand Banks. However, the current analyses show that the use of circle hooks or circle hooks in combination with mackerel bait can result in an increase in the bycatch catch of other species such as bluefin tuna, blue shark, porbeagle, and shortfin mako sharks.

Of the bycatch species presented, only blue shark are not considered overfished and are not experiencing overfishing (ICCAT 2008). Atlantic bluefin tuna and porbeagle shark are listed as a species of concern by the National Oceanic and Atmospheric Administration (NOAA) due in part to the overfished status of the stocks. Shortfin mako is the shark species most commonly retained for sale by US pelagic longline vessels in the Northwestern Atlantic. Based on the latest stock assessment, NOAA Fisheries considers the North Atlantic shortfin mako stock as experiencing overfishing, but not overfished (ICCAT 2008).

Hook Type

The way sea turtles interact with pelagic longlines differs by species. Loggerhead sea turtles are generally caught as a result of ingesting the bait and hook, while the majority of leatherback sea turtle captures results from “foul hooking,” mostly in the shoulder, armpit, and front flipper area (Watson et al. 2005, Epperly et al. 2012). Reduction of the catch rate of leatherbacks with circle hooks is likely due to the shape of the hook. Circle hooks differ from J-hooks in that the point of the hook is curved inward perpendicular to the shank. The point of J-hooks runs parallel to the shank and thus is more exposed for foul hooking. The reduction in the catch rate in loggerheads was likely because all of the circle hooks evaluated in the study were larger than the 9/0 J-hooks used as the control. 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 (i.e., mouth gape; Watson et al. 2005, Stokes et al. 2011). 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.

Circle hooks with squid bait significantly increased the catch rate of two tuna species and blue shark. Only the increase for bigeye tuna was not significant. Other studies have demonstrated that circle hook use in pelagic longline fisheries increase the catch per unit effort (CPUE) of yellowfin tuna [*Thunnus albacares* (Bonnaterre, 1788); Kerstetter and Graves 2006, Ward et al. 2009] and albacore tuna (Ward et al. 2009). Ward et al. (2009) also found a significant increase in the blue shark catch rate with circle hooks as compared to J-hooks. Results for sharks may be confounded because sharks that are gut hooked are more likely to bite off monofilament leaders and thus escape detection at haulback (Watson et al. 2005). Ward et al. (2009) observed an increase in the bite-off rate with J-tuna hooks as compared to circle hooks, but the difference was not significant.

The shape of circle hooks whereby the point is turned toward the shank is believed to have an added benefit by reducing injury to animals that are caught. Circle hooks have been shown to reduce the rate of deep hooking and increase mouth hooking in some pelagic fish such as bluefin tuna, yellowfin tuna, and billfish (e.g., Falterman and Graves 2002, Prince et al. 2002, Skomal et al. 2002, Kerstetter and Graves 2006). Experiments in the Grand Banks revealed that a greater proportion of animals captured on the 9/0 J-hook with 10°–30° offset had deeply ingested the hook as compared to those caught on circle hooks (Watson et al. 2005, Epperly et al. 2012). The probability of boating a dead swordfish, bigeye tuna, or blue shark is increased if caught on a J-hook (Epperly et al. 2012).

Bait Type and Size

For sea turtles, changes in catch rates associated with bait type may be attributed to the physical characteristics of the bait. Squid has a pliable, but tough consistency that is not easily torn from the hook. Conversely, mackerel has a firm consistency, but is easier to separate from the hook. When comparing J-hooks, the catch rate of loggerhead sea turtles is reduced with mackerel bait. Observations of captive reared loggerhead sea turtles show that while in the process of ingesting the bait, loggerhead sea turtles often pull fish bait free of the hook, unlike squid which tends to be ingested whole (Stokes et al. 2011). With both J-hooks (JM and JTM), mackerel bait had a lower catch rate of leatherbacks than squid bait, although the reduction by JTM was not significant. The observed reduction in leatherback interactions with mackerel bait is believed to be the result of the fish bait shielding the hook point (Watson et al. 2005).

Mackerel bait led to an increase in catches of swordfish, porbeagle, and shortfin mako sharks for all hook combinations except for swordfish catch by J-tuna hooks, which decreased significantly. These results are consistent with studies showing that porbeagle and shortfin mako sharks in the western North Atlantic feed primarily on teleost fish (Stillwell and Kohler 1982, Kohler 1987). While scombrids are a common part of swordfish diets, cephalopods are the primary dietary component of swordfish in the western North Atlantic (Stillwell and Kohler 1982). However, the results of our study indicate that, in an opportunistic situation, swordfish may prefer mackerel to squid.

Blue shark, bigeye tuna, and albacore tuna showed a reduction in catch rate with mackerel bait. It is not clear if the reduction in blue shark was a result of bait preference or sharks pulling the bait free from the hooks prior to ingesting the hooks. While cephalopods make up the primary component of blue shark diets, locally abundant pelagic and demersal fish are also consumed (Kohler 1987). In a comparison of squid vs mackerel bait on pelagic longlines off of Brazil, Broadhurst and Hazin (2001) found that a higher portion of the hooks baited with mackerel resulted in lost bait with no catch. The incidence of lost baits with no catch was not recorded in the present study. However, if blue sharks attempt to bite mackerel bait in two as opposed to ingesting it whole, there will be a higher likelihood of tearing the mackerel bait free of the hook, which could explain the observed reduction in catch. The reduction in bigeye tuna and albacore tuna catch may relate to the relative size of the mackerel bait as compared to the squid. The mackerel used in the experiment were 200–500 g as compared to the 150–300 g squid. Research by Ménard et al. (2006) indicates that bigeye and yellowfin tunas feed on small prey relative to body size. With an increase in body size, the mean and maximum size of prey increases. Even so, regardless of tuna size, small prey continue to make up a large proportion of the diet.

Other Factors

Our results demonstrate that changes in spatial and temporal fishing strategies can affect catch composition. The effect of sea surface temperature on catch rates indicates that fishing cooler waters can reduce the catch rate of loggerheads, leatherbacks, and shortfin mako without significantly impacting the catch of swordfish, but may also increase the bycatch of bluefin tuna, blue shark, and porbeagle shark, while negatively impacting the catch rate of bigeye tuna.

Several confounding factors make interpretation of the effects of total soak time and daylight soak time problematic. There was a reverse causality issue that occurred with the more common species such as blue shark and swordfish, i.e., an increase in catches of one or both species was associated with an increase in total and daylight soak time due to the increased time required to haul the gear. Due to the setting and hauling practices of the fishery, we also expect confounding effects between total soak time and daylight soak time. Vessels typically set the gear at sunset and start hauling after sunrise. In most cases, an increase in total soak time results in an increase in daylight soak time. Seasonal changes in the photoperiods during the experiment can also result in changes in total and daylight soak times. Therefore, soak time effects may be masked by seasonal changes in catch rates.

The experimental treatments of 18/0 circle hooks with squid and mackerel bait were tested in both 2002 and 2003 to evaluate the annual variability of the results. Model year effects indicated that catch rates were significantly lower in 2003 for all species except for loggerheads and porbeagle shark. However, the treatment effects presented in the combined 2002 and 2003 analysis are consistent with the 2002 results presented in Watson et al. (2005).

In conclusion, the development of selective fishing technologies and strategies can be effective in reducing the ecological impact of fishing practices by reducing bycatch and discards. Since the NED research project began in 2001, there has been a great deal of additional research to evaluate the effects of hook type on target and bycatch (e.g., Yokota et al. 2006, Piovano et al. 2009, Ward et al. 2009, Sales et al. 2010, Swimmer et al. 2010). However, only a limited umber of studies have evaluated bait type in pelagic longline fisheries (e.g., Broadhurst and Hazin 2001, Watson et al. 2005). We have demonstrated that changes in hook and bait type can be used to reduce ecological impact of pelagic longline fishing on sea turtle populations. However, the effective catchability of swordfish was maintained only with the change from squid to mackerel bait. Bait type, therefore, can have as pronounced effect on the catch composition of pelagic longlines as the type of hooks used. Understanding the individual and interactive effects of the terminal components of the gear may allow us to optimize the harvest of target catch while reducing the impact on non-target species.

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