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PERFORMANCE OF NON-OFFSET AND 10° OFFSET 18/0 CIRCLE HOOKS IN THE UNITED STATES PELAGIC LONGLINE FISHERY

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ABSTRACT

Industry standard fishing hooks used prior to 2004 during US commercial pelagic longline (PLL) fishing were the 8/0–10/0 J-hooks with a 20°–25° offset—a lateral deviation of the hook point relative to the hook shaft. However, federal regulations enacted in 2004 require the US PLL industry to employ circle hooks allowing up to 10° offset during fishing operations. Until recently, there have been no studies directly comparing the performance of non-offset and 10° offset circle hooks in commercial PLL applications. Our study alternated non-offset and 10° offset circle hooks along the gear length on individual PLL deployments in the western North Atlantic, Gulf of Mexico, and Windward Passage in the Caribbean Sea. The study compared the relative performance of both hook types in terms of: (1) catch rates, (2) percent mortality, and (3) the percentage of deep-hooked target and bycatch species. For swordfish, *Xiphias gladius* (Linnaeus, 1758), several experiments indicate: (1) marginally higher catch rates, (2) significantly lower mortality, and (3) significantly less deep hooking on non-offset than 10° offset circle hooks. Most of the performance differences for blue marlin, *Makaira nigricans* Lacépède, 1802, were insignificant; however, one study produced significantly higher mortality on 10° offset than non-offset circle hooks. The present study suggests that, relative to non-offset circle hooks, 10° offset circle hooks may reduce fishing efficiency and can counteract the conservation benefits commonly associated with circle hooks (e.g., lower mortality). However, additional research is required to assess the effects of offset hooks on tunas, billfishes, and elasmobranchs.

Fishery activities play a substantial role in reducing stocks of marine species (Myers and Worm 2003, Jørgensen et al. 2007). Pelagic longline (PLL) fishing targeting swordfish, *Xiphias gladius* (Linnaeus, 1758), and tunas, *Thunnus* spp., often captures marine animals that have little or no commercial value (Beerkircher et al. 2002, Falterman and Graves 2002, Watson et al. 2005, Kerstetter and Graves 2006a), which and are referred to as bycatch (NOAA 1996). Typical bycatch encountered during PLL fishing includes, but is not limited to, sea turtles, sharks, billfishes, marine mammals, seabirds, and undersized individuals of targeted species (i.e., regulatory discards, NOAA 1996). Interactions between these animals and PLL gear are considered a primary source of mortality (Domeier et al. 2003, Myers and Worm 2003, Cramer 2004, Kerstetter and Graves 2006a), and the highest source of fishing mortality for billfishes (Restrepo et al. 2003, Uozumi 2003, Serafy et al. 2005).

Prior to 2004, the historical industry-standard fishing hooks used during US commercial PLL fishing were the 8/0, 9/0, or 10/0 J-hooks with a 20°–25° offset (Watson et al. 2005). Offset is defined as the lateral deviation of the hook point relative to the main plane of the hook shank (Prince et al. 2007). Recent federal regulations allow

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commercial PLL fishers in the Atlantic to use 18/0 or larger circle hooks with up to 10° offset (NOAA 2004). Circle hooks are believed to reduce mortalities of bycatch species because the hooks are designed to capture fish in the corner of the mouth or jaw and thus avoid deep-hooking and associated hook injury (Skomal 2002, Cooke and Suski 2004, Cramer 2004, Watson et al. 2005, Swimmer et al. 2010). Increasing the degree of offset is thought to be: (1) more effective in hooking and retaining fish as well as facilitating baiting (Watson et al. 2005, Foster et al. 2012), and (2) an important factor affecting the incidence of deep hooking and subsequent mortality (Prince et al. 2002, Horodysky and Graves 2005, Prince et al. 2007, Swimmer et al 2010). However, until recently there have been no studies directly comparing the performance of the two circle hook types (i.e., 10° offset and non-offset) in PLL gear applications.

Cooke and Suski (2004) provide a comprehensive review of circle hook performance compared to a variety of other hook types used in both fresh water and the marine environment. They reported mixed results for catch rates, but overall lower mortality, less gut hooking (i.e., shallow hooking or more fish hooked in the corner of the mouth), and less bleeding with circle hooks compared to J-hooks, especially for tunas and billfishes. They concluded that circle hooks are an effective tool for conservation, but application to specific fisheries and species should be based on fishery and species-specific data. There have been several studies evaluating the relative performance of circle hooks vs J-hooks for large pelagic fishes, including some during recreational rod-and-reel fishing (Prince et al. 2002, 2007, Skomal et al. 2002, Domeier et al. 2003, Horodysky and Graves 2005) and others during PLL fishing (Hoey 1996, Falterman and Graves 2002, Watson et al. 2005, Kerstetter and Graves 2006a,b, Diaz 2007, Mejuto et al. 2007). However, circle hooks come in many varieties of shapes, sizes, and degrees of offset, and there have been few studies evaluating the effects of these differences on hook performance metrics (Prince et al. 2002, Watson et al. 2005) and currently only one study directly comparing 14/0 offset to non-offset circle hooks in the shallow-set Costa Rican (Pacific) based PLL fishery (Swimmer et al. 2010).

The specific objectives of our study were to evaluate the relative performance of non-offset and 10° offset 18/0 circle hooks employing a paired experimental design during PLL fishing. For target (Xiphiidae and Scombridae) and bycatch taxa (Istiophoridae and Elasmobranchii) we compared catch rates, mortality (condition upon gear retrieval), and the incidence of deep-hooking.

Materials and Methods

Experimental PLL fishing, using commercial vessels and crews, was conducted during 2003, 2004, and 2005. The 2003 and 2004 trials were conducted in the area of the Windward Passage, which lies between the Republic of Haiti (Hispaniola) and the Republic of Cuba. The 2005 trials were conducted as a Cooperative Research Project (CRP; see below for additional detail) throughout the western North Atlantic and Gulf of Mexico (Fig. 1). Gear configurations varied according to year, area, and target species (Table 1).

The hooks used during our study (Lindgren-Pitman, Inc.) were 10° offset (model: LPCIRSS10) and 0° non-offset (model: LPCIRSS0) 18/0 circle hooks (Fig. 2). The two hook types were alternated (i.e., paired) along the entire length of the PLL gear to balance factors that might affect the catchability of each hook type, including hook position, fish abundance and patchiness, environmental factors (e.g., water temperatures), and temporal differences in

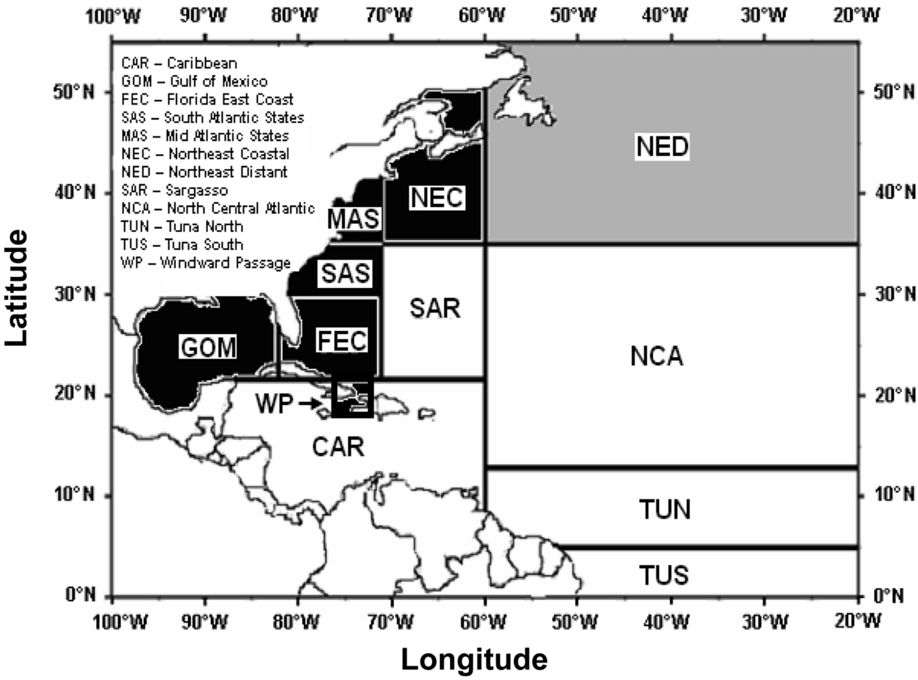

Figure 1. National Oceanic and Atmospheric Administration (NOAA) North Atlantic statistical reporting areas showing general area of experimental pelagic longline fishing in the Windward Passage during 2003 (10 sets) and 2004 (10 sets) as well as the NOAA Cooperative Research Project (total 118 sets; area shaded black).

fishing operations. Bait consisted of mackerel (*Scomber scombrus* Linnaeus, 1758) or squid (*Ilex* spp.) and either bait type was used exclusively during a single gear deployment. Catch rate analysis by hook type required accurate hook identification; therefore, branchlines (i.e., gangions) were color coded to allow identification of lost hooks resulting from tangles, bite-offs, cut-offs, etc. Gear deployed during all studies involved a mainline buoyed to the surface by a floatline with floats and branchlines with baited hooks connected to the mainline (Fig. 3).

Gear Specifics for Windward Passage 2003 and 2004.—The experimental vessel used during the 2003 and 2004 studies was a 16.75 m fiberglass commercial pelagic longline fishing vessel targeting swordfish. Longline gear was deployed at dusk and allowed to soak overnight. Gear retrieval commenced in the early morning before sunrise and generally lasted until late morning or early afternoon. The fishers employed "American style" pelagic longline fishing techniques using a large monofilament mainline (455 kg test strength and 3.5 mm diam) on a large hydraulic spool (about 1.5 m axial length). The mainline was passively deployed as hooks and floats were attached while the boat was moving forward. Longline gear was usually recovered in the reverse direction of deployment depending on weather and oceanic conditions. Fish were harvested as gear was recovered and then stored on ice for the fresh fish market in the US and all bycatch was discarded.

Each complete set of the longline gear consisted of several sections partitioned by single-side-band radio beacons used to locate and track the fishing gear. Each section was buoyed by five air-filled polyethylene low-drag floats (known as "polyballs"). Light sticks were placed on every branchline about 3.7 m from the hook. Each float line was 18.3 m in length and each branchline was 20.1 m in length. A 60-g lead swivel was attached at the end of each branchline

Table 1. Fishing strategy, including target species, gear configuration, number of sets, bait type, and mean sea surface temperature (SST) employed during experimental pelagic longline fishing in the Caribbean Sea (Windward Passage), and Gulf of Mexico and the western North Atlantic (Cooperative Research Project, CRP). hpb = gear configuration (hooks per basket).

Experiment	Target	Number of sets	hpb	Bait type	Mean SST (°C)
Windward Passage 2003	Swordfish (*Xiphias gladius*)	10	4	Squid (*Illex* sp.)	30.0
Windward Passage 2004	Swordfish (*Xiphias gladius*)	10	15	Squid (*Illex* sp.), Boston mackerel (*Scomber scombrus*)	27.9
CRP 2005	Swordfish (*Xiphias gladius*)	78	5	Boston mackerel (*Scomber scombrus*)	24.1
CRP 2005	Bigeye tuna (*Thunnus obesus*)	40	7	Squid (*Illex* sp.)	27.6

and connected to a 1.8-m leader for an overall gear length of about 40 m. Branchline and leader material consisted of nylon monofilament (136 kg test, 1.8 mm diam).

Experimental Design Windward Passage 2003.—During 2003, 10 sets with a mean (±SD) of 46.9 ± 2.8 km of longline fishing gear were deployed with about 560 hooks per set. We conducted near-surface fishing typical of the US PLL fleet targeting swordfish by deploying four hooks between surface buoys (known as hooks per basket or hpb).

Experimental Design Windward Passage 2004.—Gear configuration was the same in 2003 and 2004, except for the number of hooks per basket (Table 1). During 2004, we employed a deeper gear configuration similar to the Japanese PLL fleet targeting deeper-dwelling tunas by deploying 15 hpb. Seven (of 10) sets averaged 41.7 ± 6.3 km of mainline deployed with about 532 hooks per set. Inclement weather towards the end of the 2004 research cruise resulted in three (of 10) shorter sets which averaged 33.4 ± 1.0 km with about 380 hooks per set.

Cooperative Research Project 2005.—During April–June 2005, NOAA Fisheries conducted a cooperative research project (CRP) with six commercial PLL fishers operating in the western North Atlantic and Gulf of Mexico (GOM). In total, 78 PLL sets targeting swordfish and 40 PLL sets targeting bigeye tuna, *Thunnus obesus* (Lowe, 1839), were deployed. Of the 78 experimental sets targeting swordfish, 14 were deployed in Northeast Coastal (NEC) statistical area, 22 were deployed in the South Atlantic States (SAS) area, 20 were deployed in the Florida East Coast (FEC) area, and 22 were deployed in the GOM (Fig. 1, Table 2). Of the 40 experimental sets targeting bigeye tuna, 29 were deployed in the NEC and 11 were deployed in the Mid-Atlantic States (MAS) area (Fig. 1, Table 2). All vessels participating in the research were required to adhere to spatial regulations and use standard commercial longline gear configurations and fishing practices that were allowed for the region. Experimental fishing required a minimum deployment of 450 experimental and control hooks alternated along the entire length of the gear with uniform spacing within a set. Additional sections of fishing gear were allowed to be deployed as long as fishers followed all requirements of the experimental design. Fishing targeted species in accordance with current NOAA Highly Migratory Species (HMS) regulations. Each vessel was required to carry a NOAA authorized Fishery Observer for data collection.

CRP 2005 Swordfish-Directed Experiments.—Experimental commercial PLL fishing vessels targeting swordfish were required to use Atlantic mackerel (*S. scombrus*) as bait. However, a potential confounding variable occurred from different baiting techniques employed for each hook type during this portion of the study. Specifically, non-offset circle hooks were single-hooked through the eye of the mackerel bait while 10° offset circle hooks were threaded through head and body of the mackerel bait. Gear configurations varied depending

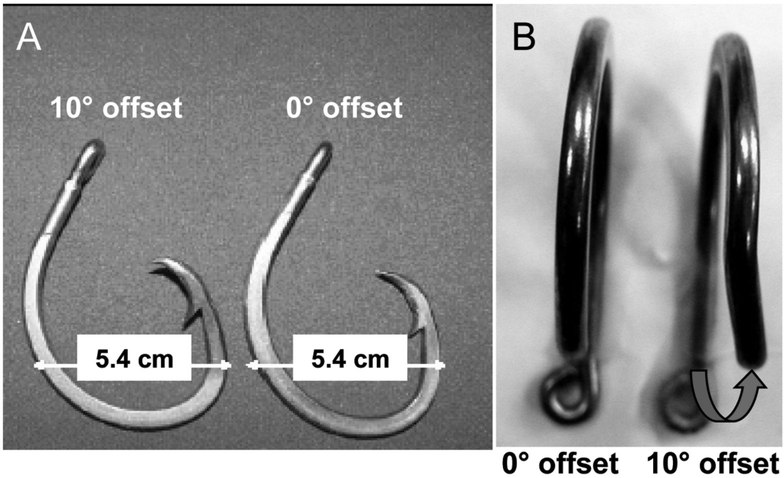

Figure 2. Two 18/0 circle hook types allowed by the US federal government during commercial pelagic longline fishing. (A) Lateral view comparing circle hook diameter (photo courtesy of J Watson); (B) frontal view showing 10° angle created by offsetting the hook.

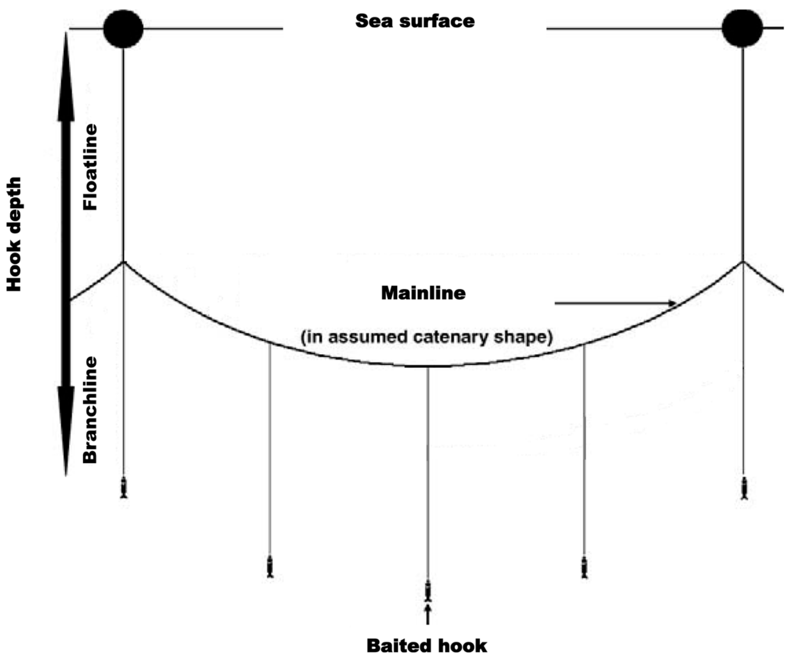

Figure 3. Schematic representation of a single basket of typical near-surface pelagic longline fishing gear (modified from Rice et al. 2007).

Table 2. Regional distribution of pelagic longline fishing along the east coast and Gulf of Mexico for swordfish-directed sets (total = 78) and bigeye tuna-directed sets (total = 40) during the National Oceanic and Atmospheric Administration Cooperative Research Project in 2005.

Fishing area	Swordfish directed sets (78)	Bigeye tuna directed sets (40)
Northeast Coastal (NEC)	14	29
Mid Atlantic States (MAS)	0	11
South Atlantic States (SAS)	22	0
Florida East Coast (FEC)	20	0
Gulf of Mexico (GOM)	22	0

on the fishing location, but always employed 5 hpb. The latitude of Cape Hatteras (about 35°15´N) was chosen to distinguish fishing in the MAS and SAS areas (Fig. 1). Vessels targeting swordfish north of Cape Hatteras were required to use 9 m branchlines and 14.6 m leaders (total gear length = 23.6 m). Vessels targeting swordfish south of Cape Hatteras were required to use 18.3 m branchlines with 22 m leaders (total gear length = 40.3 m). Vessels targeting swordfish in the GOM were required to use 18.3 m branchlines with 45.7 m leaders (total gear length = 64 m).

CRP 2005 Bigeye Tuna–Directed Experiments.—All PLL fishing targeting bigeye tuna occurred north of Cape Hatteras and vessels were required to use whole squid (*Illex* spp.) and identical baiting techniques on non-offset and 10° offset circle hooks. A single gear configuration was deployed when targeting bigeye tuna and consisted of 7 hpb, 18.3-m branchlines, and 22-m leaders (total gear length = 40.3 m assuming no catenary).

Statistical Analysis.—Differences in performance metrics (i.e., catch rate, mortality, or hook location) between hook types were categorized as significant ($P < 0.05$), marginally significant ($0.05 \leq P < 0.10$), and non-significant ($P \geq 0.10$). Teleost fishes were categorized into three families: swordfish (Xiphiidae), tunas (Scombridae), and marlins and sailfish (Istiophoridae). All cartilaginous fishes (sharks and pelagic rays) were grouped into the subclass Elasmobranchii. Species-specific hook-bait performance metrics were evaluated only for the istiophorid billfish and swordfish. Statistical analysis was performed using Statistical Analysis Software (SAS 1990, version 9.1.3 Service Pack 4, SAS Institute, Inc.).

Catch rate analysis included catch per unit effort—number of fish per 1000 hooks—for all taxa, and for swordfish specifically, total biomass, economic biomass (i.e., weight of fish retained for commercial sale), and discard biomass per 1000 hooks. In most cases, fish weight was recorded and analyzed as dressed weight; however, lengths were recorded for undersized swordfish (both estimated and measured lower-jaw fork length) and converted to weight using gender specific swordfish conversions reported by Arocha (1997). Frequency analysis, stem and leaf, box plots, and the Shapiro-Wilk tests for normality (SAS 1990) were employed to determine the distribution of the catch rate data. All catch rate distributions were highly skewed toward the origin due to the preponderance of zero catch reported for each hook type (i.e., "zero-inflated" data). Because the catch rate data were not normally distributed and variances were heterogeneous, a non-parametric alternative to the paired *t*-test [i.e., Wilcoxon Signed Rank Test (WSR)] was employed (Ott 1993). The non-parametric paired *t*-test approach was considered as the most parsimonious statistical procedure as it: (1) required no assumptions that data were drawn from a given probability distribution nor assumptions about the form (e.g., linearity) of response to independent variable influence; and (2) accounted for both measured (e.g., water temperature) and unmeasured (e.g., prey fish densities, ocean current velocities) differences among sets that might confound results.

The effect of each hook type on fish mortality at harvest—the condition of the animal at boatside—was evaluated by determining the proportion of dead fish and reported as a mortality percentage. The Cochran-Mantel-Haenszel chi-square test (CMH χ^2) was used to determine significant differences among the proportions of live and dead fish for each hook type.

This statistical test was chosen due to the stratified character of the data and its robustness to relatively low sample sizes (SAS 1990, Agresti 1996, Kerstetter and Graves 2006a).

The effect of each hook type on the hooking location was evaluated by observation of the position of the hook in the harvested fish. Deep hooking events were recorded if the leader was not visible in the mouth or throat of the fish (i.e., beyond the buccal cavity and gills). No attempts were made to determine hook locations on live bycatch intended for release. The CMH χ^2 test was used to test for significant differences between the proportions of deep hooking events for each hook type.

Results

Swordfish.—With the exception of CRP swordfish-directed sets, catch was higher on non-offset than 10° offset 18/0 circle hooks. Seventy-three swordfish were captured (41 on non-offset, 32 on 10° offset) during the Windward Passage 2003 and 67 swordfish were captured (40 on non-offset, 27 on 10° offset) during the Windward Passage 2004. In total, 1172 swordfish were captured (574 on non-offset, 598 on 10° offset) during the CRP 2005 swordfish-directed sets and 339 swordfish were captured (183 on non-offset, 156 on 10° offset) during the CRP bigeye tuna–directed sets (Table 3). Swordfish catch per unit effort was marginally higher on non-offset than 10° offset 18/0 circle hooks during the Windward Passage 2004 (WSR: $P = 0.06$) and CRP bigeye tuna–directed sets ($P = 0.08$, Fig. 4A). Catch rates were not significantly different between hook types for the CRP swordfish-directed fishing or the Windward Passage 2003. There were no significant differences between hook types in total swordfish biomass and swordfish economic biomass catch rates; however, the catch rate for swordfish discard biomass was marginally higher ($P = 0.08$) on non-offset hooks during the Windward Passage 2004 (Fig. 5).

Swordfish mortality (i.e., the proportion of swordfish dead upon gear retrieval) was significantly lower ($P = 0.04$) on non-offset than 10° offset circle hooks during the Windward Passage 2003 fishing trials (Fig. 4A). Due to the marginally higher catch rate for swordfish discard biomass on non-offset as compared to 10° offset circle hooks mentioned above (Fig. 5), we further evaluated the condition (i.e., proportion of dead) of discarded fish by hook type, but no significant differences were revealed (Fig. 6). The proportion of deep-hooked swordfish was significantly lower ($P = 0.001$) on non-offset than 10° offset 18/0 circle hooks during the CRP swordfish-directed fishing (Fig. 4A).

Billfishes.—Twenty-two billfishes were captured (9 on non-offset, 13 on 10° offset) during the Windward Passage 2003 and seven billfishes were captured (3 on non-offset, 4 on 10° offset) during the Windward Passage 2004. In total, 191 billfishes were captured (76 on non-offset, 115 on 10° offset) during the CRP 2005 swordfish-directed sets and 23 billfishes were captured (11 on non-offset, 12 on 10° offset) during the CRP bigeye tuna–directed sets. Billfish catch was dominated by sailfish (*Istiophorus platypterus* Shaw, 1792; total = 133) during the CRP swordfish-directed sets and was significantly higher ($P = 0.03$) on 10° offset (86) vs non-offset (47) circle hooks (Table 3). There were no significant differences between hook types for billfish mortality or deep hooking during any of the experiments (Fig. 4B).

For blue marlin, about 59% (30) and 33% (17) were captured during near surface PLL fishing conducted during the swordfish-directed trials (i.e., the CRP 2005 and the Windward Passage 2003, respectively). Only 8% (4) and 2% (1) of blue marlin were

Table 3. Species-specific catch by each hook type during experimental pelagic longline fishing from 2003 to 2005 along the western North Atlantic including the East Coast and the Gulf of Mexico (Cooperative Research Project, CRP), and the Caribbean Sea (Windward Passage, WP). SWO = swordfish; BET = Bigeye tuna.

	Species-specific catch (no.)											
	Swordfish		Blue marlin		Sailfish		White marlin		Tuna		Elasmobranchs	
Experiment	0° offset	10° offset	0° offset	10° offset	0° offset	10° offset	0° offset	10° offset	0° offset	10° offset	0° offset	10° offset
WP 2003	41	32	7	10	0	0	2	3	16	22	7	5
WP 2004	40	27	2	2	0	0	1	2	10	10	4	3
CRP 2005 SWO	574	598	17	13	47	86	12	16	36	32	458	410
CRP 2005 BET	183	156	0	1	0	3	11	8	139	124	169	194

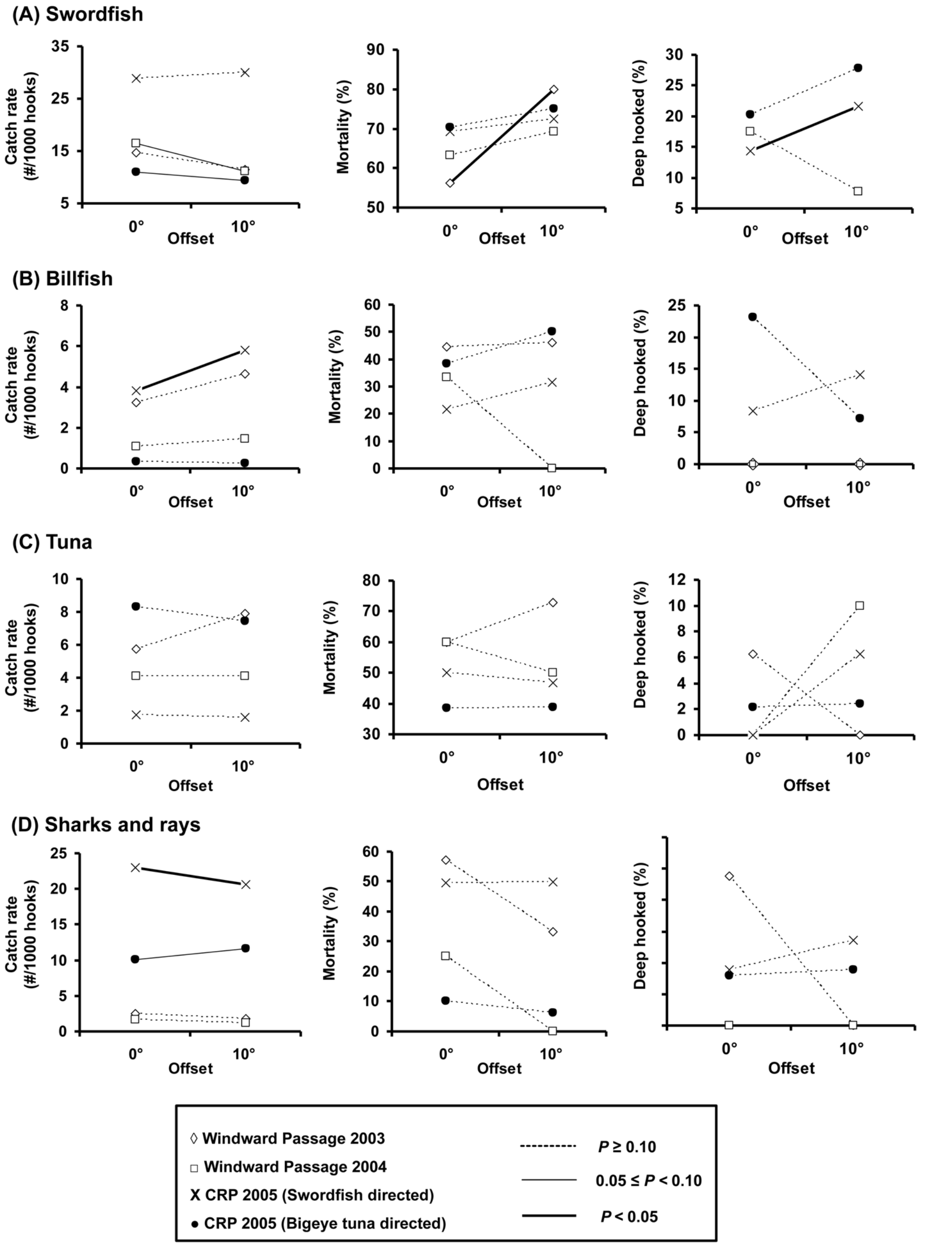

Figure 4. Comparison of catch rate (number per 1000 hooks), mortality (%), and deep hooking (%) between non-offset (0°) and 10° offset 18/0 circle hooks for (A) swordfish (family: Xiphiidae), (B) marlins and sailfish (family: Istiophoridae), (C) tuna (family: Scombridae), and (D) sharks and rays (subclass: Elasmobranchii). CRP = Cooperative Research Project.

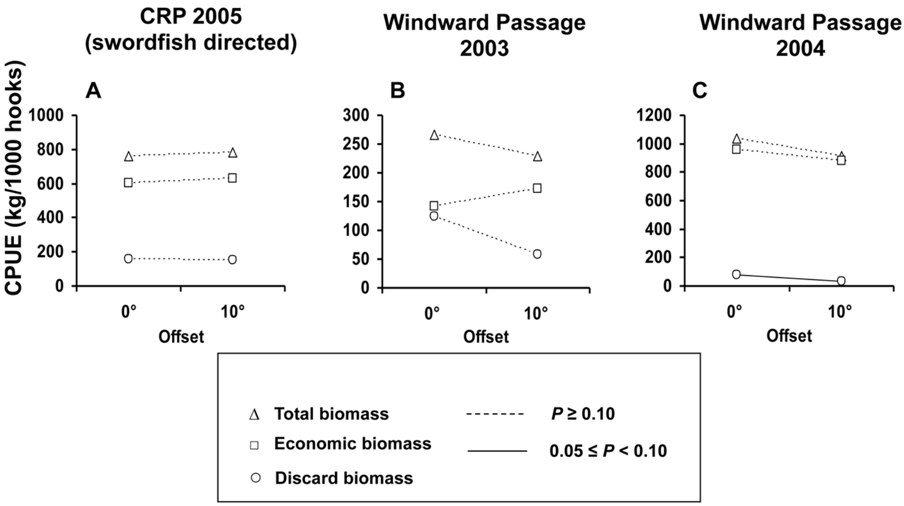

Figure 5. Comparison between non-offset (0°) and 10° offset 18/0 circle hooks on swordfish, *Xiphias gladius,* biomass catch per unit effort (kg per 1000 hooks) for total biomass, economic biomass (fish retained for sale), and discard biomass (damaged and undersized swordfish released alive and discarded dead). (A) Cooperative research project (CRP) 2005; (B) Windward Passage 2003; (C) Windward Passage 2004.

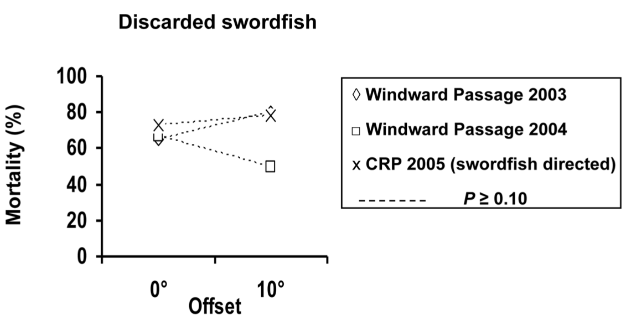

Figure 6. Comparison between non-offset (0°) and 10° offset 18/0 circle hooks on swordfish, *Xiphias gladius,* discard biomass mortality (%) during experimental pelagic longline fishing in the Caribbean Sea (Windward Passage), Gulf of Mexico, and western North Atlantic. CRP = Cooperative Research Project.

captured during deeper PLL fishing conducted during the Windward Passage 2004 and bigeye tuna–directed CRP 2005, respectively. There were no significant differences in catch rates or deep hooking percentages between hook types, but there was significantly higher mortality ($P = 0.04$) on 10° offset circle hooks than non-offset circle hooks during the CRP swordfish-directed sets (Fig. 7A).

There were no sailfish captured in the Windward Passage during 2003 or 2004. Ninety-eight percent (133) of the sailfish captured during trials were caught during the 2005 CRP swordfish-directed trial (Table 3). Species-specific results for sailfish indicated a significantly higher catch rate ($P = 0.004$) on 10° offset than non-offset circle hooks, but there were no significant differences in mortality or deep hooking (Fig. 7B).

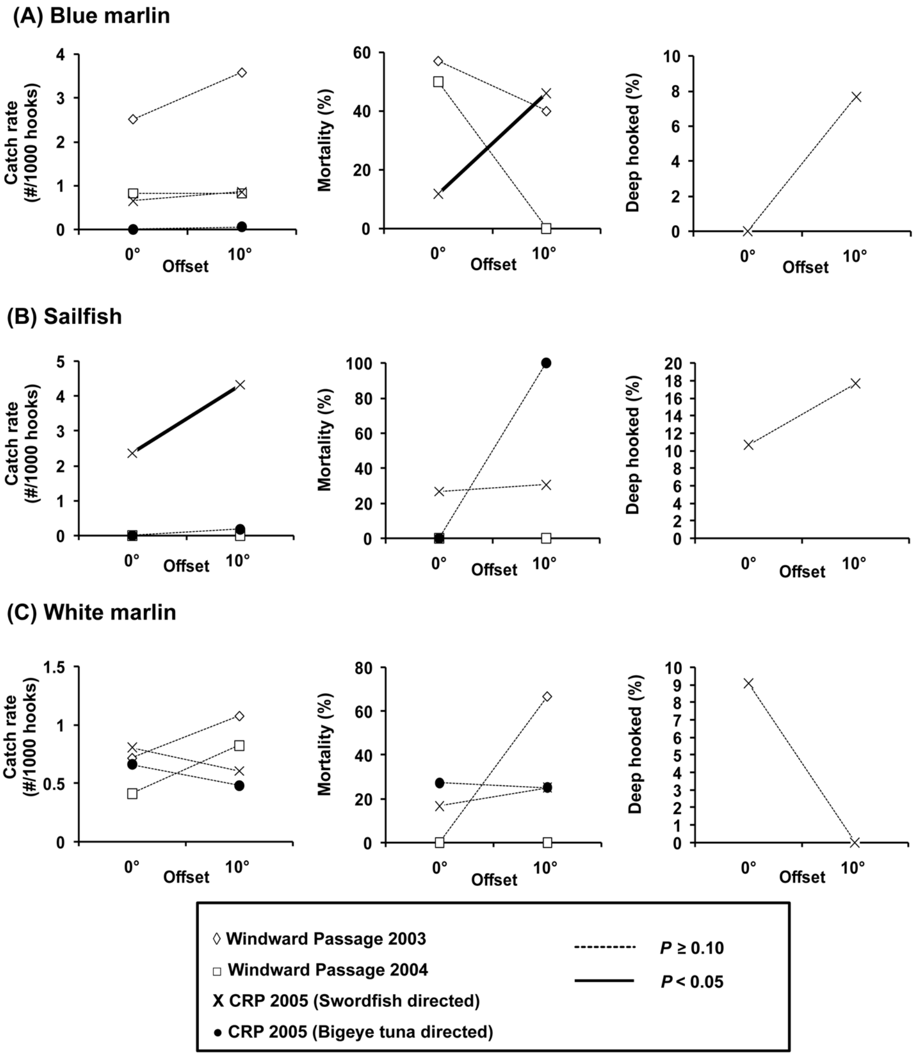

Figure 7. A species specific comparison of catch rate (number per 1000 hooks), mortality (%), and deep hooking (%) between non-offset (0°) and 10° offset 18/0 circle hooks for (A) blue marlin, *Makaira nigricans*; (B) sailfish, *Istiophorus platypterus*; (C) white marlin, *Tetrapturus albidus*. CRP = Cooperative Research Project.

Fifty-five white marlin were captured (26 on non-offset, 29 on 10° offset) and there were no significant differences in catch rate, mortality, or deep hooking (Table 3, Fig. 7C). Interestingly, unlike blue marlin and sailfish, which were mostly captured during near surface longline fishing (i.e., Windward Passage 2003 and CRP swordfish-directed trials), white marlin catch was evenly distributed between the near surface (60%) and deeper fishing (40%) gear configurations (Table 3).

Tuna.—In total, 38 tuna were captured (16 on non-offset, 22 on 10° offset) during the Windward Passage 2003 trial and 20 were captured (10 on non-offset, 10 on 10° offset) during the Windward Passage 2004 trial; 67 tuna were captured (36 on non-offset, 32 on 10° offset) during the CRP 2005 swordfish-directed sets and 263 tuna were captured (139 on non-offset, 124 on 10° offset) during the CRP bigeye tuna–directed sets (Table 3). There were no significant differences during any of the experimental fishing trials with regard to hook type, mortality, or deep hooking (Fig. 4C).

Sharks and Rays.—In total, 12 sharks and pelagic rays were captured (7 on non-offset, 5 on 10° offset) during the Windward Passage 2003 and seven were captured (4 on non-offset, 3 on 10° offset) during the Windward Passage 2004 trial. In total, 868 sharks and pelagic rays were captured (458 on non-offset, 410 on 10° offset) during the CRP 2005 swordfish-directed sets and 363 were captured (169 on non-offset, 194 on 10° offset) during the CRP bigeye tuna–directed sets (Table 3). Catch rates for sharks and pelagic rays were significantly higher (P = 0.03) on non-offset than 10° offset circle hooks during the swordfish-directed CRP sets. However, the opposite trend was observed during the bigeye tuna–directed CRP with marginally higher (P = 0.08) catch reported on 10° offset vs non-offset (Fig. 4D). Mortality and deep hooking were not significantly different between hook types for any experiment.

Sea Surface Temperature.—Mean sea surface temperature (SST) varied indirectly with latitude for each experimental fishing trial and ranged from 24.1 to 30.0 °C (Table 1). The CRP bigeye tuna–directed fishing trials experienced the lowest mean SST while the Windward Passage 2003 trial experienced the highest SST.

Discussion

The present study is among the first to directly compare catch characteristics of non-offset and 10° offset 18/0 circle hooks in a paired experimental design. Although there was relatively high variability in trends between components of our study (i.e., across study years and regions), we documented general trends of the performance of these two hook types with respect to catch rate, mortality, and hook location.

Circle hooks are designed to capture fish in the corner of the mouth (Cooke and Suski 2004); however, Malchoff et al. (2002) suggested that offsetting circle hooks may negate normal "jaw-hooking" and as a result the conservation benefits typically associated with them. Prince et al. (2002) compared smaller circle hooks (7/0) with various degrees of offset (severe offset = 15°, minor offset = 4°, non-offset = 0°) on sailfish catch, hook location, and bleeding rate during recreational rod-and-reel live bait fishing off south Florida. They found no significant differences in catch percentage associated with the three types of circle hooks. However, generally consistent with our study, they found that severe offset (15°) circle hooks had a significantly higher incidence of deep hooking events and that minor (4°) and non-offset (0°) had a significantly higher incidence of hooking sailfish in the corner of the mouth. Watson et al. (2005) conducted a study similar to ours in that they evaluated identical terminal gear, targeted swordfish, and employed similar fishing methods (i.e., near surface PLL fishing). They evaluated the effectiveness of fishing gear modifications, including non-offset and 10° offset 18/0 circle hooks with several bait types (e.g., Atlantic mackerel, *S. scombrus*, shortfin squid, *Illex* spp.) directly against the industry standard J-hooks during PLL fishing in the NED. However, Watson et al. (2005) inferred differences between the two circle hook types (in terms of target, non-target, and bycatch catch rates and hook location) without directly testing for them (i.e., via alternating non-offset and 10° offset circle hooks within the same longline set). They reported significantly higher catch rates (kg per 1000 hooks) for swordfish and significantly higher percentage of gut hooking on 10° offset than non-offset circle hooks baited with squid. They found no significant differences in bigeye tuna catch rate or hook location between these two hook types when baited with squid. Contrary to the previous findings of Watson et al. (2005), when we considered catch rates for swordfish by weight, we found no significant differences between the two circle hook types except during the Windward Passage 2004 trial, where discarded swordfish biomass was marginally higher on non-offset circle hooks. This result was not entirely unexpected given the higher catch rate reported for swordfish on non-offset circle hooks in the Windward Passage 2004 trial. This indicates that many of the swordfish captured during this trial were undersized or damaged. Moreover, when we analyzed swordfish catch rates by the number of fish captured per 1000 hooks, we found marginally higher catch rates on non-offset vs 10° offset 18/0 circle hooks during the Windward Passage experiments in 2004 and the CRP bigeye tuna–directed sets. One possible explanation for differing results in the Watson et al. (2005) study is that they "did not directly compare the two circle hook types" by alternating hooks within the same longline set. Rather, differences were inferred from temporally separated treatments. However, fishing results between longline sets can be highly variable (Swimmer et al. 2010), even when using the same gear and configuration (Rice et al. 2007). Therefore, comparisons between fishing from temporally separated gear deployments may have low power to detect differences between hook types, even when all variables that affect catchability are kept constant. Alternating the two circle hook types during a single gear deployment results in paired performance metrics that are robust to variations during PLL fishing because each hook type is exposed to virtually identical conditions in the environment and fish availability. In addition, some published studies of catch rate by biomass include only processed fish (i.e., dressed fish) and do not report valuable information on regulatory discards, such as undersized or damaged fish, where weights are not measured (e.g., Watson et al. 2005). For this reason, we suggest future studies analyze catch rates by both the number and weight of fish captured for each treatment tested, including regulatory discard weights via length weight conversion so these important data are considered.

Watson et al. (2005) reported significantly higher catch rates for blue shark (*Prionace glauca* Linnaeus, 1758) and a significantly higher percentage of gut hooking on 10° offset vs non-offset circle hooks baited with squid. Our study reported mixed results for sharks and rays with significantly higher catch on non-offset than 10° offset circle hooks during the swordfish-directed CRP sets and the opposite trend during the bigeye tuna–directed CRP with a marginally higher catch reported on 10° offset vs non-offset. One possible explanation for the mixed results for sharks and rays, relative to catch rates by hook type for other taxa, is that shark catch rates are highly affected by bite-offs during PLL fishing (Godin et al. 2012). All PLL fishers during our study employed nylon monofilament branchline material, which is easily severed when bitten by sharks. Numbers of bite-offs were not analyzed during our study, but future studies focusing on the effects of offsetting circle hooks on shark catch rates should consider employing more durable fishing material (e.g., wire leaders). Another possible explanation could be due to differing species-specific responses of sharks and rays. Since elasmobranch data were pooled, species-specific responses were not analyzed, but may have influenced catch by hook type.

Gut hooking has been identified as an important factor influencing the mortality of fish captured as a result of fishing pressure (Prince et al. 2002, Skomal et al. 2002, Domeier et al. 2003, Cooke and Suski 2004, Horodysky and Graves 2005, Prince et al. 2007, Swimmer et al. 2010). The condition or fate of animals interacting with PLL gear is important not only for animals intended for release from the fishing gear (i.e., bycatch, catch-and-release, etc.), but also for the quality of the target species because live fish at the time of harvest fetch a higher market value (Cramer et al. 1981). Our results on hooking location are consistent with those reported by Watson et al. (2005) and indicated that 10° offset circle hooks result in significantly higher mortality during Windward Passage 2003 and more deep (or gut) hooking events during CRP swordfish-directed trails than non-offset circle hooks for swordfish. Increased deep hooking events on 10° offset relative to non-offset circle hooks is most likely due to exposure of the hook point as it exits the animal. In addition, tenuous snagging of the hook point in soft tissue as it exits the animal may interfere with the ability of the circle hook to engage and capture the animal in the corner of the mouth. This may explain the marginally higher swordfish catch rates observed on non-offset vs 10° offset circle hooks during the Windward Passage 2004 and CRP bigeye tuna–directed trials during our study.

Lotti et al. (2011) suggested that temperature has a positive correlation with mortality during bottom longline fishing. However, those results may not be applicable to commercial pelagic longline fishing. The present study observed the highest percent mortality (approximately 80%) for swordfish on 10° offset circle hooks and the lowest percent mortality (approximately 50%) for swordfish on non-offset circle hooks during the same experimental trial (Windward Passage 2003) which had the warmest mean SST reported. Therefore, differences in percent mortality during our study may be attributed more to hook effect than any temperature related effects, especially since both hook types were deployed during the same set and in similar environmental conditions during each trial.

During the CRP swordfish-directed sets, non-offset and 10° offset circle hooks were directly compared and, although identical baits were used, different baiting techniques were employed (i.e., single eye-hooked on non-offset and threaded bait on 10° offset). These differences in baiting styles are not negligible and may have a substantial effect on the catchability of each hook type. These confounding baiting techniques may have introduced bias in the CRP swordfish-directed results.

In conclusion, as demand for pelagic resources continues to grow with the increasing global population, it is important to thoroughly understand factors that influence fishing efficiency and associated conservation efforts. Understanding how differences in terminal gear (i.e., hooks) affect the catchability and the condition of the catch is of specific concern because: (1) the terminal gear is usually the immediate point of interaction between the gear and the pelagic animals during fishing, and (2) terminal gear can be regulated, providing a realistic management tool. Results reported here indicate that offsetting circle hooks by 10° resulted in no appreciable increase in catch rates for swordfish. In fact, marginally higher catch rates were reported on non-offset circle hooks relative to 10° offset circle hooks in two experiments. Further, in several experiments, 10° offset circle hooks increased the incidence of deep hooking and mortality relative to non-offset circle hooks for swordfish and in one experiment for blue marlin. These findings suggest that fishing success is not improved and conservation efficiency can be reduced when 10° offset circle hooks are allowed during PLL fishing targeting swordfish. To examine the generality of the findings presented here, more research with homogenous baits and baiting techniques and high sample sizes is warranted to directly compare offset and non-offset circle hook performance.

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