Errata

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Corrections

The title of this article should read as follows:

A comparison between circle hook and J hook performance in the dolphinfish, yellowfin tuna, and wahoo troll fishery off the coast of North Carolina

For the general text and figure and table legends:

The correct species name for skipjack tuna is *Katsuwonus pelamis* and the correct common name for *Euthynnus alletteratus* is "little tunny."

A comparison between circle hook and J hook performance in the dolphinfish, yellowfish tuna, and wahoo troll fishery off the coast of North Carolina

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Abstract—We compared numbers of strikes, proportions of fish that hooked up after strikes, proportions of fish that stayed on hook (retained) after hook up, and numbers of fish caught between circle and J hooks rigged with dead natural fish bait (ballyhoo) and trolled for three oceanic predator species: dolphinfish (*Coryphaena hippurus*), yellowfin tuna (*Thunnus albacares*), and wahoo (*Acanthocybium solandri*). Interactions were compared between circle and J hooks fished on 75 trips by two user groups (charter and recreational fishermen). Hooks were affixed to three species-specific leader types most commonly fished in this region: monofilament (dolphinfish), fluorocarbon (tuna), and wire (wahoo). Numbers of fish caught per trip and three potential mechanisms that might influence numbers caught (i.e., number of strikes, proportion of fish hooked, and proportion retained) were modeled with generalized linear models that considered hook type, leader type, species, user (fishing) group, and wave height as main effects. Hook type was a main effect at the catch level; generally, more fish were caught on J hooks than on circle hooks. The effect of hook type on strike rates was equivocal. However, J hooks had a greater proportion of hook-ups than did circle hooks. Finally, the proportion of fish retained once hooked was generally equal between hook types. We found similar results when data from additional species were pooled as a "tuna" group and a "mackerel" group. We conclude that J hooks are more effective than circle hooks at the hook-up level and result in greater numbers of troll-caught dolphinfish, tunas, and mackerels.

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Literature on a variety of species and fishing strategies provides evidence that catch rates with circle hooks can be maintained (but rates of deep hooking are reduced) when compared with catch rates with conventional J hooks (Cooke and Suski, 2004). Studies on the relative effectiveness of hook types for billfishes have revealed that circle hooks offer a conservation benefit (reduced rates of deep hooking) while maintaining catch rates comparable to those with J hooks for both troll and longline fisheries (Serafy et al., 2009). For example, Prince et al. (2002) found that trolled circle hooks rigged with natural baits maintained catch rates of Atlantic sailfish (*Istiophorus platypterus*) but reduced rates of deep hooking compared with catch rates with J hooks. Similarly, Horodysky and Graves (2005) found that white marlin (*Kajikia albida*) caught on trolled circle hooks had no mortality compared to 35% mortality on J hooks. Based on these findings, a rule was instituted by the National Marine Fisheries Service (NMFS) that required the use of non-offset circle hooks when trolling natural or combination baits (natural bait and skirt) in Atlantic billfish tournaments (Federal Register, 2006). The intent of this regulation was to reduce deep hooking, and thus rates of catch-and-release mortality, in white and blue marlin (*Makaira nigricans*).

Outside of directed tournaments, Atlantic billfishes are generally not the only targets in charter and recreational troll fishery of North Carolina. For many ports, billfishes are only a rare bycatch. In North Carolina, dolphinfish (*Coryphaena hippurus*), yellowfin tuna (*Thunnus albacares*), and wahoo (*Acanthocybium solandri*) are the predominant targets of recreational and charter trip troll fisheries in Gulf Stream waters (senior author, personal observ.). Dolphinfish and yellowfin tuna are the top two species by weight landed in the North Carolina recreational fishery and together represent over half of the total recreational landings in the state (NCDMF, 2010). Recreational and charter anglers harvest 93% of the roughly 4.5 million kg of dolphinfish landed annually along the U.S. Atlantic coast and roughly 90% of wahoo landed in U.S. South Atlantic waters (North Carolina through Florida) and Mid-Atlantic waters (New York through Virginia) (SAFMC, 2003). Trolling is the predominant fishing method for pelagic fishes in Gulf

Stream waters off of North Carolina. Catch composition of dolphinfish, yellowfin tuna, and wahoo in this troll fishery varies widely among vessels, seasons, and locations in the Gulf Stream.

There is concern in the charter boat industry that circle hook regulations (developed for and based on billfish), if ever mandated outside of U.S. Atlantic billfish tournaments, would negatively impact catch rates of dolphinfish, yellowfin tuna, and wahoo. Chartering an offshore fishing trip in the southeastern United States is an expensive endeavor (~$2000/day; senior author, personal observ.) and reductions in catch may have economic influences on charter fishing businesses. Success of the offshore troll fishery relies on clientele having a reasonable chance to catch and keep fish that are highly valued as seafood. In North Carolina, there are few charter captains willing to use or experiment with circle hooks when targeting non-billfish species because there is a widespread perception that trolling circle hooks for non-billfish species results in reduced catch rates, and therefore greater chances for customer dissatisfaction, compared with J hooks. The charter ocean fishing industry in North Carolina includes roughly 750 vessels and receives $65 million annually in for-hire fees (Dumas et al., 2009). Economic ramifications of requiring circle hooks outside U.S. Atlantic billfish tournaments have not been quantified.

Our purpose in undertaking this study was to determine the effects of using circle hooks on catch levels of non-billfish species in the U.S. southeastern offshore troll fishery in comparison with catch levels with J hooks. Mechanisms that might explain differences or similarities in catch between hook types were also examined. Questions were the following: 1) Did predators strike circle and J hook rigged baits at similar rates?; 2) Once struck, did circle and J hook rigged baits have similar proportions of hook-ups?; and 3) Once hooked up, did circle and J hook rigged baits have similar proportions of retained fish (brought to the boat)?

Materials and methods

Fishing techniques workshop

In November 2007 we convened a workshop attended by state and federal biologists, fishery managers, charter boat captains and mates, private boat anglers, and billfish tournament directors. The purpose of the workshop was to select hook types, hook styles, rigging techniques, and fishing techniques (see below) that could be used to compare trolled circle and J hooks in Gulf Stream waters off North Carolina during troll fishing days aboard charter vessels.

Defining and selecting circle and J hooks was a central part of the workshop. A circle hook was defined as having the point perpendicular to the hook shank. A J hook was defined as having the point and point shank parallel to the hook shank. We selected circle and J hooks that would be comparable in bend diameter (gap between hook shank and point shank). For both hook types, we selected barbed hooks with zero offset and straight hook eyes (eye parallel to the hook shank). The circular shape, hook point turned perpendicularly toward the shank, and zero offset insured that the circle hooks we selected conformed to the National Marine Fisheries Service definition in the current billfish tournament regulations (Federal Register, 2006). Other hook characteristics (hook size, hook gauge, gap width, and shape) were selected to avoid compromising the action and durability of the trolled dead whole fish (ballyhoo [*Hemiramphus brasiliensis*]). Participants decided that circle and J hooks with a gap width large enough that allowed space between the bait and hook for hooking fish but with a relatively low profile (by virtue of the gauge of hook wire) would be most appropriate for testing.

Bait rigging and fishing techniques

The bait rigging techniques for each non-billfish species presented at the workshop were those used by the local charter industry. Circle and J hooks were embedded in ballyhoo except for directed trips for dolphinfish, when circle hooks were rigged externally (Fig. 1). Other differences in bait rigging and fishing techniques are described below by species. Hook sizes and styles, leader characteristics, and rigging techniques differed slightly on recreational trips because these fishermen often troll with smaller hooks and different rigging techniques from those used by charter captains.

For charter and recreational trips targeting dolphinfish we used Mustad 9175 7/0 J hooks (Mustad, Gjövik, Norway[1]) that were rigged inside ballyhoo; the chin weight was affixed to 30 cm of rigging wire. We used Eagle Claw 2004ELG 8/0 circle hooks (Eagle Claw Fishing Tackle Co, Denver, CO) rigged externally to the ballyhoo with a 7-g chin weight and swivel at the top of the head, with 30-cm of rigging wire (no pin). The leader was 1.8 m of 36 kg of monofilament attached to the standing line with a 31-kg Sampo ball-bearing swivel (Sampo Inc., Barneveld, NY). The leader was attached to the hook by using a loose crimp with tag end opposite the point (Fig. 1A). We used lever drag reels affixed to "thirty pound-class" stand-up rods at all locations. Reels were spooled with a 14-kg test Diamond® monofilament line (Diamond Fishing Products, Pompano Beach, FL). The drag upon strike of a fish was set just above "free spool" (reel gear not engaged) with the clicker in the "on" position. The drag during the fight of a fish (regardless of species) was roughly 6.4 kg. Baits were dropped back (line allowed to come off the spool with no drag) to missed fish (that struck) immediately after the strike. Recreational rigging techniques for dolphinfish were similar to those used on the

[1] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

charter vessel except that 1) circle and J hooks were one size smaller.

Charter trips targeting yellowfin tuna used Mustad 7692 9/0 J hooks and Eagle Claw 2004ELG 9/0 circle hooks rigged inside ballyhoo, with 7-g chin weights affixed to a pin. Hook and leader were secured to the bait with a rubberband (for wahoo see next paragraph). The leader was 9 m of 36 kg of clear fluorocarbon leader through which a blue and white Seawitch lure (C&H Lures, Jacksonville, FL) with a 14-g lead head was threaded and positioned above the eye of the hook (Fig. 1B). The leader was attached to the standing line with a 36-kg SPRO power swivel (SPRO Corp., Kennesaw, GA). Both hook types were attached to the leader with a loose crimp with the tag end opposite the point. We used Penn "50-wide" reels (Penn, Philadelphia, PA) affixed to "fifty pound class" stand-up rods at all locations. Reels were spooled with 27-kg Diamond® line. The drag upon strike was set at roughly 4.5 kg while the drag during fight (regardless of fish species) was set to roughly 6.4 kg. Baits were dropped back to missed strikes and then only until a fish picked up the bait. Recreational rigging techniques for yellowfin tuna were similar except that 1) circle hooks were the same type and style but one size smaller, 2) J hooks were Mustad 3407, 7/0 size, 3) the fluorocarbon leader was 3.7 m long, and 4) "thirty pound class" stand up rods were used.

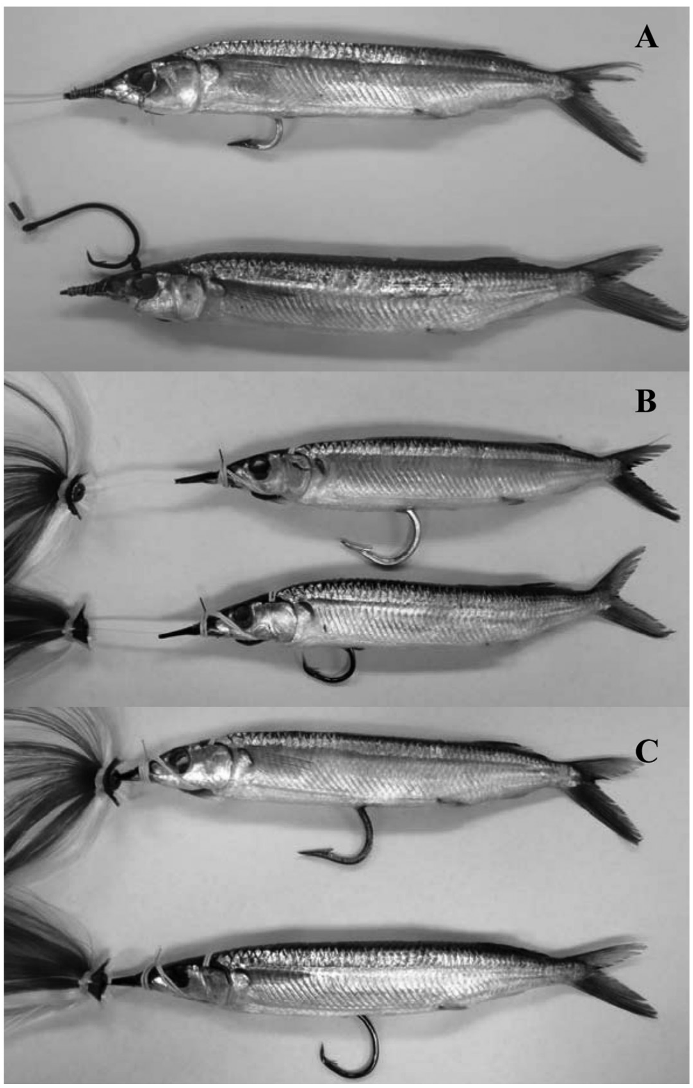

Figure 1

Circle and J hook rigging techniques and leader types used in trolling ballyhoo for (**A**) dolphinfish (*Coryphaena hippurus*) on monofilament leaders, (**B**) yellowfin tuna (*Thunnus albacares*) on fluorocarbon leaders, and (**C**) wahoo (*Acanthocybium solandri*) on single-strand wire leaders. The circle hook is the bottom hook type in each of the three photographs.

Charter trips targeting wahoo used Mustad 7731A 8/0 J hooks and Eagle Claw 2004 ELG 9/0 circle hooks rigged inside ballyhoo with a 7-g chin weight and pin that comprised part of the wire leader. The leader was 3.7 m of #9 (41 kg) piano wire (Fig. 1C) with haywire twists for attaching leader to a hook at one end and for forming a loop at other end; the leader was attached to the standing line with a 59-kg ball bearing clip swivel. As with yellowfin tuna, a blue and white Seawitch lure with a 14-g lead head was threaded through the leader and positioned above the eye of the hook. The same rod and reel types used for yellowfin tuna were used for wahoo. Baits were dropped back to missed strikes and then only until a fish picked up the bait. Recreational rigging techniques for wahoo were similar to those used for charter fishing except that 1) circle hooks were one size smaller; 2) J hooks were Mustad 3407, 7/0 size and 3) "thirty pound class" stand up rods were used.

Data collection

Circle and J hooks were trolled side-by-side for both the charter and recreational groups. Fishing occurred in Gulf Stream and nearby ocean waters off North Carolina. The two charter boats were employed in order to simulate a typical for-hire fishing operation in this region. Each of the two captains and mates used for charter trips in this study had over 20 years experience in this fishery, as well as experience rigging and trolling circle hooks for billfishes. Fishing aboard a research vessel was conducted to simulate a recreational operation where fishermen have no mate to coordinate the fishing operation (i.e., to coordinate, rig, and check baits; monitor and clear lines; check drags; and hook and gaff fish), but instead do these activities themselves. Before each charter trip, the captain and first author determined which non-billfish species would be targeted and adjusted the tackle class, leader, and rig type accordingly; the first author made this determination for the recreational trips. This determination was based on water temperature, time of year, and fishing reports that indicated which species we would be most likely to interact with. We fished monofilament, fluorocarbon, and wire leaders a total of 6, 12, and 18 days on the charter vessels, and 18, 7, and 14 days on the recreational vessel. There were not equal numbers of days fished between the two user groups. At most, one boat trip was taken per day.

On each of the two charter vessels we fished pairs of standing rods (held by fixed rod holders) from four positions. These four pairs were flat lines, short outriggers (riggers), long riggers, and bridge poles. On windy days, rods were not fished from the bridge because of increased likelihood of tangles in the lines. On days directed for wahoo, we used in-line planers on the flat-line rods in order to fish baits deeper in the water column and elicit a greater number of interactions with this species. We randomly selected which side of the boat (port or starboard) would receive the circle and J hook treatment on each day of charter fishing.

We fished two pairs of lines simultaneously aboard the research vessel. These pairs were flat lines and poles fished from rod holders on a canopy “t-top.” For each day of fishing on the recreational vessel, we staggered hook types so that a hook type on a flat line was on the side of the boat opposite that same hook type on the t-top.

The three vessels used to collect data trolled at between six and seven knots (regardless of species targeted). Chains of combined artificial lures consisting of four 23-cm long squids ending with a blue and white Iland Lure® (L&S Bait Company, Inc., Largo, FL)-ballyhoo bait combination were deployed as teasers (no hooks) from each vessel during the collection of data. A chain of pink squids was deployed on the starboard side of the boat and a chain of green squids was deployed on the port side of the boat. Baits were medium ballyhoo that were replaced upon washout.

We recorded fish total length (mm) when it was possible to associate a fish length with a hook type. This was not always possible because of multiple fish being caught and placed in fish box at nearly the same time. Hooking location was recorded for all captured fish.

Data analysis

Four response variables were measured: numbers caught, numbers of strikes, proportion hooked up, and proportion retained. Numbers of fish caught reflected the cumulative results for the strike, hook-up, and retention levels. A fish interacting with the gear in a manner such that the line was pulled from the outrigger clip or that engaged the reel clicker when no clip was used was considered a strike (Prince et al., 2002). A fish that had been hooked for 10 seconds after striking was considered a hook-up. A retained fish was one where the leader was touched or the fish put into the boat (“boated”). The proportion of fish that hooked up was relative to the number that struck (Prince et al., 2002); similarly, the proportion of fish that were retained on the hook was relative to the number that hooked up.

Strikes and hook-ups for fish not caught or visually identified were included in the analysis. When the appearance of a struck bait (e.g., bite marks), water temperature, time of year, fishing location, fish behavior (jumping), and order of fish landed each day indicated a particular species, we attributed these interactions to that species. When these six factors did not combine to indicate a particular species, these interactions were considered to be from an unidentified species. We allocated strikes and hook-ups from unidentified fish to each species in the same proportion as that for fish boated for that day of fishing. At each level of interaction we found similar best fitting models for data that excluded or included unidentified fish (Rudershausen et al., 2010).

Generalized linear models (GLMs) were used to determine the effects of hook type (circle or J), leader type (monofilament, fluorocarbon, or wire), species (dolphinfish, yellowfin tuna, or wahoo), user group (recreational or charter), wave height, and potentially important interactions on the numbers of fish caught and each of three mechanisms leading to a caught fish. We constructed a sequence of Poisson GLMs for the numbers caught and numbers of strikes data sets. For hook-up and retention data, we used binomial GLMs to represent the conditional nature of the hook-up and retention processes (e.g., the number of fish that hooked up in a given trip was conditional on the number that struck). In each case, hook type, leader type, species, and user group were treated as categorical variables, whereas wave height was treated as a continuous variable. Species caught on days where they were not the main target were included in all analyses and are referred to as “nondirected” species. At each level of interaction, plots were constructed to help better visualize the relative effectiveness of circle and J hooks on directed leader types.

We collected the same response variable data for other species that have feeding styles similar to those of yellowfin tuna and wahoo to provide additional data to clarify trends in relative hook-type effectiveness. The four model sets described above were also fitted to data sets that included blackfin tuna (*Thunnus atlanticus*), skipjack tuna (*Euthynnus pelamis*), and false albacore (*Euthynnus alletteratus*), which were combined with yellowfin tuna data to form a “tuna” group (family Scombridae, tribe Thunnini), and king mackerel (*Scomberomorus cavalla*) and Spanish mackerel (*Scomberomorus maculatus*), which were combined with wahoo data to form a “mackerel” group (family Scombridae, tribe Scomberomorini). This additional model fitting kept dolphinfish as a single-species group.

We adopted an information-theoretic perspective to compare the parsimony of relatively simple models that we believed would help determine relative effectiveness of each hook type at catching fish and on mechanisms during the fish-hook interaction (strike, hook-up, and retention). We inspected data plots to determine factors other than hook that contributed to variability in catch rates. Base models for each level of fish interaction were then constructed without hook main effects and hook interactions. For each of these potential base models we calculated a quasi-Akaike's information criterion (QAIC; Burnham and Anderson, 2002). QAIC was computed instead of AIC because of potential over-dispersion of the data used as the response variable in each model (Burnham and Anderson, 2002). At each level of fish interaction, we selected the base model with the lowest QAIC value. The most parsimonious base models had 1) main effects (excluding hook) plus a leader-species interaction at the catch level; 2) main effects (excluding hook) plus leader-species and species-user interactions at the strike level; 3) main effects (excluding hook) plus a leader-user interaction at the hook-up level; and 4) main effects (excluding hook) plus a species-user interaction at the retention level. After the base model was selected, we developed incrementally more complex models that then included a hook effect and interaction terms between hook and other factors. This sequential model building allowed us to determine if the main factor of interest—hook type—covaried with other factors potentially influencing interactions with fishes. Any models with three-way interactions also included two-way subinteractions. $QAIC_i$ values were then used to compare fits among all i models (including the base model) at each level of fishing interaction to help determine the combination of predictors that best explained variation in the data. The $\Delta QAIC$ value for each model was calculated as the difference between any particular model ($QAIC_i$) and the minimum QAIC for the best fitting model in the set ($QAIC_{min}$). The model with the $QAIC_{min}$ value was, for each model set, considered to be the one representing the data adequately with the fewest parameters; however, we regarded models that differed by <~ 4 $\Delta QAIC$ as all having reasonable support (Burnham and Anderson, 2002). We also computed Akaike weights (w_i) for each model to help gauge the relative support for each model in the model set; the value of w_i varies between 0 and 1, with a greater value indicating that a particular model better fits the data. See Burnham and Anderson (2002) for equations used to compute QAIC and w_i.

Highly parameterized models often resulted in singular Hessian matrices, indicating that one or more parameters were nonidentifiable. However, we retained these models in each model set because our primary goal was to obtain parsimonious predictions of how hook type affected catch rates. In an information-theoretic context, over-parameterized models would simply be penalized for requiring additional parameters to explain the same amount of variation in the data and therefore would be unlikely to be selected with QAIC.

The selection of base models and development of more complex models incorporating a hook main effect and hook interactions by using data on taxa (e.g., dolphinfish, "tunas," and "mackerels") followed the process used for the three species. Base models at each level of fish interaction were the same as in the species analyses described above with the exception of the retention level, where a model consisting of main effects (except hook) plus a leader-species interaction best fitted the taxa data.

We computed the relative effectiveness of circle and J hooks (effect size) by comparing predicted circle and J hook catch rates of dolphinfish, yellowfin tuna, and wahoo on their respective directed leader types. Effect size was calculated for each catch model with a positive Akaike weight (w_i) (see *Results* section). Effect size (ES) for each of these models was computed as

$$ES = \frac{\mu_x}{\mu_y}, \qquad (1)$$

where μ_x and μ_y = the predicted mean catch-per-trip values on circle and J hooks, respectively.

Effect size theoretically ranges from zero to greater than one. An effect size less than, equal to, or greater than one indicates that circle hooks are less, equally, or more effective than J hooks, respectively. The variance (σ^2) about each effect size was calculated as

$$\sigma^2 = \frac{\sigma_x^2}{\mu_y^2} + \frac{\left(\mu_x^2\right)\left(\sigma_y^2\right)}{\mu_y^4}, \qquad (2)$$

where σ_x^2 and σ_y^2 are the variances about the mean predicted mean catch-per-trip values of circle and J hooks. The values for user and wave were held constant (at 0.48 and 0.79 m, respectively) when computing effect size for the three species-leader combinations from each aforementioned catch model. The effect size from each model was weighted by the relative w_i value. Weighted effect size values from each model were summed to determine an overall effect size for each of the three species caught on its directed leader type. This model-averaging procedure was repeated to compute overall variance about each average effect size; model averaging for variance was conducted by multiplying each model's variance by the squared value of the Akaike weight (w_i^2). Computations of predicted effect sizes and associated variances were repeated with the data on taxa.

For each species, we compared median lengths between hook types with a median ranks test (α=0.05). Data were combined across leader types and user groups for each of these size-based analyses. For each species, we compared rates of jaw (mouth) and deep hooking (gut, gills, or eyes) among hook types using a chi-square square test of independence.

Table 1

Number of fish caught on circle and J hooks from 39 recreational and 36 charter trips trolling both hook types with natural and combination baits offshore of North Carolina, 2006–10. Each number (no.) and percent (%) column is specific to user group (recreational vs. charter) and hook type (circle vs. J). Each column of % values adds up to 100%.

	Recreational				Charter			
	Circle		J		Circle		J	
Species	No.	%	No.	%	No.	%	No.	%
Dolphinfish (*Coryphaena hippurus*)	35	63.6	71	77.2	45	40.2	73	38.8
Yellowfin tuna (*Thunnus albacares*)	7	12.7	5	5.4	25	22.3	47	25.0
Wahoo (*Acanthocybium solandri*)	0	0.0	1	1.1	20	17.9	22	11.7
Blackfin tuna (*Thunnus atlanticus*)	0	0.0	0	0.0	14	12.5	26	13.8
King mackerel (*Scomberomorus cavalla*)	8	14.5	3	3.3	0	0.0	4	2.1
Barracuda (*Sphyraena barracuda*)	1	1.8	0	0.0	1	0.9	3	1.6
Spanish mackerel (*Scomberomorus maculatus*)	0	0.0	3	3.3	0	0.0	0	0.0
False albacore (*Euthynnus alletteratus*)	2	3.6	6	6.5	4	3.6	5	2.7
Greater amberjack (*Seriola dumerili*)	0	0.0	1	1.1	0	0.0	1	0.5
Bluefish (*Pomatomus saltatrix*)	0	0.0	1	1.1	0	0.0	0	0.0
Atlantic sailfish (*Istiophorus platypterus*)	1	1.8	0	0.0	2	1.8	4	2.1
White marlin (*Tetrapturus albidus*)	0	0.0	1	1.1	0	0.0	0	0.0
Blue marlin (*Makaira nigricans*)	0	0.0	0	0.0	0	0.0	1	0.5
Skipjack tuna (*Euthynnus pelamis*)	0	0.0	0	0.0	1	0.9	2	1.1
Bullet mackerel (*Auxis* spp.)	1	1.8	0	0.0	0	0.0	0	0.0

Results

Catch composition

The three most abundant species captured on recreational trips were dolphinfish, yellowfin tuna, and king mackerel, which together constituted 91% of the catch on circle hooks and 86% on J hooks. The three most abundant species captured on charter trips were dolphinfish, yellowfin tuna, and wahoo, which together constituted 80% of the catch on circle hooks and 76% on J hooks. Blackfin tuna were commonly caught on charter trips, constituting 13% of the catch on circle hooks and 14% of the catch on J hooks. Billfishes made up 1% of the catch on recreational trips and 3% of the catch on charter trips (Table 1). Pooling across both user groups, we found that 74% of dolphinfish were caught on monofilament leaders, 96% of yellowfin tuna were caught on fluorocarbon leaders, and 98% of wahoo were caught on wire leaders; that is, the vast majority of individuals from each species were captured on the respective directed leader type. Species identity could not be determined in 14.0% of strike and 2.9% of hook-up interactions over the course of the study.

Comparisons of catch and examination of mechanisms influencing catch

Hook type influenced catch rate (Fig. 2). For the three-species analysis of catch rate, the base model plus a hook main effect received majority support (Table 2). For directed leaders, J hooks caught more dolphinfish than circle hooks for both recreational and charter groups. Higher catches on J hooks were also observed in the charter group for yellowfin tuna; however, there was no clear hook effect within the recreational group for yellowfin tuna or wahoo or charter group for wahoo. Partial support for models containing hook-user and hook-species interactions confirms these observations (Table 2). The hook-leader interaction also had support and was most obvious in the dolphinfish data where the hook effect was not consistent across leader types (Fig. 2). Model fitting to numbers-caught data with taxa (i.e., dolphinfish, tunas, and mackerels) provided similar results to those for species data (Table 2; Fig. 3); the base model plus a hook main effect received majority support as the best fitting model and models that included hook-user, hook-leader, and hook-species interactions had QAIC values within four units of the best fitting model. Tunas were caught more often on J hooks and fluorocarbon leaders than other hook-leader combinations. Mackerels were caught slightly more often on J hooks than circle hooks, and most often on wire leaders (Fig. 3).

The first mechanism contributing to catch was strike. Hook type had little effect on strikes for each of the three species examined (Fig. 4). No single model received majority support when fitted to strike data for the three species and the base model with a hook factor received only slightly greater support than the base model without the hook parameter (Table 3). Models

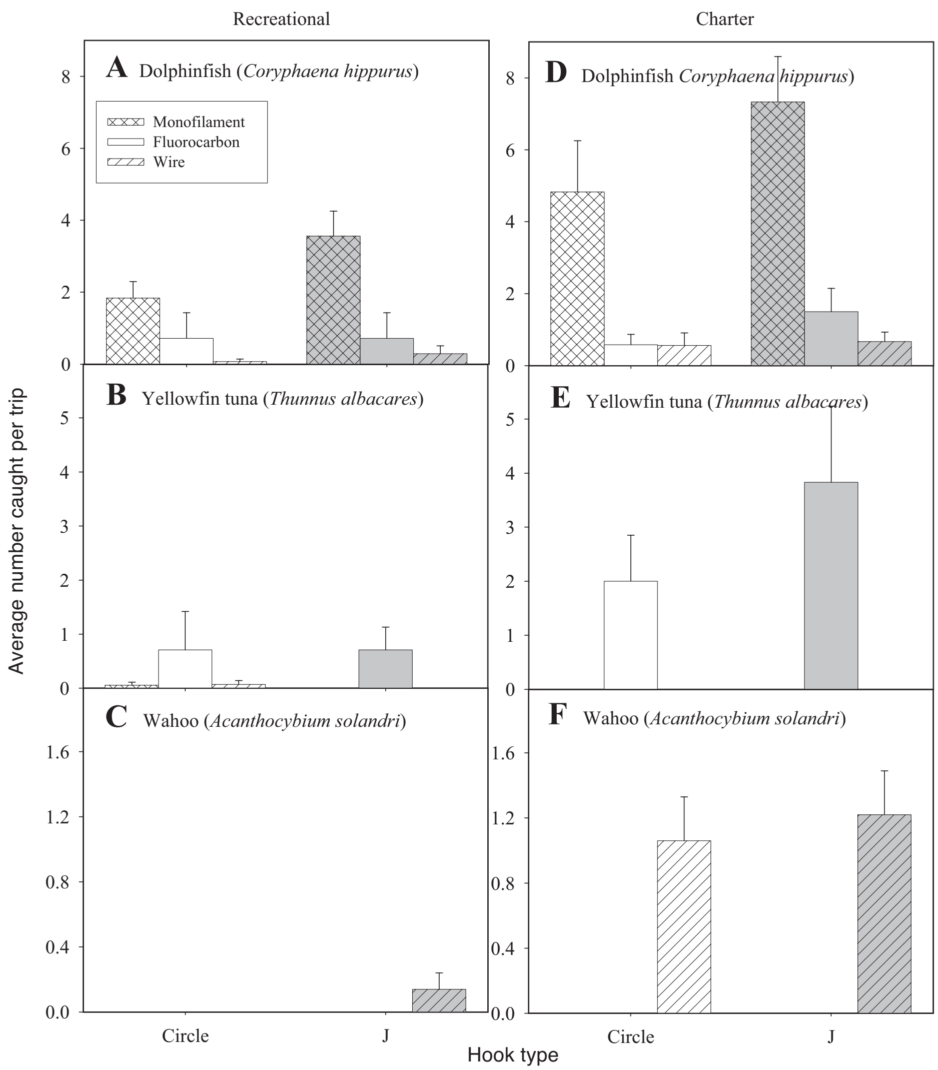

Figure 2

Plots of the average catch per trip (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for each species are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **D–F**]) and species (dolphinfish [*Coryphaena hippurus*] [A, D], yellowfin tuna [*Thunnus albacares*] [B, E], and wahoo [*Acanthocybium solandri*] [C, F]). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+species+user-group+leader-type combination indicates no catch.

with hook-user, hook-leader, and hook-species interactions each received a relatively small amount of support. Greater numbers of strikes occurred 1) on charter boats (owing to a greater number of rods fished), 2) when using monofilament leaders, and 3) from dolphinfish than any other species. As with the three species data, there was little difference in the average strikes per trip between circle and J hooks for each taxa (Fig. 5). Similarly, the model that best fitted strike data for the taxa was the base model with hook, but the base model without hook received only slightly less support (Table 3; Fig. 5). Models with hook-user, hook-species, and hook-leader interactions received relatively minor support.

The second mechanism contributing to catch was hook-up. J hooks were more effective at hooking fish for many user group-species combinations (Fig. 6). Hook was a main effect in the model that best fitted the proportional hook-up data (Table 4). Models that received less support included hook-user, hook-species, hook-leader, and hook-species + hook-user interactions. The base model received no support. There was a reduction of hook-ups for dolphinfish when circle hooks were used on both recreational and

Table 2

Candidate models fitted to catch-per-trip data for three species (dolphinfish [*Coryphaena hippurus*], yellowfin tuna [*Thunnus albacares*], and wahoo [*Acanthocybium solandri*], and taxa [dolphinfish, tunas, and mackerels]) when trolling circle and J hooks in Gulf Stream waters off North Carolina. Quasi-Akaike information criterion (QAIC) was used to evaluate model performance, with the lowest value indicating the most parsimonious model. Categorical predictor variables included hook type (hook), leader type (leader), species or taxa, and user group (user). Wave height was used as a continuous predictor variable. *K*=number of parameters for each model; *w*=Akaike weight. Base models included all predictor variables with exception of hook and any hook interactions; see *Methods* section for a full description of base models. ΔQAIC values ~<4 were considered models with reasonable support.

Interaction	Data type	Distribution	Model	*K*	QAIC	ΔQAIC	*w*
Catch: species	Count	Poisson	base + hook	13	356.77	0.00	0.54
			base + hook + hook*user	14	358.42	1.65	0.23
			base + hook + hook*leader	15	360.49	3.72	0.08
			base + hook + hook*species	15	360.90	4.14	0.07
			base + hook + hook*user + hook*leader	16	361.98	5.21	0.04
			base + hook + hook*species + hook*user	16	362.54	5.77	0.03
			base + hook + hook*species + hook*leader	17	364.91	8.15	0.01
			base + hook + hook*species + hook*leader + hook*species*leader	21	373.59	16.83	0.00
			base	12	385.14	28.37	0.00
Catch: taxa	Count	Poisson	base + hook	13	477.17	0.00	0.55
			base + hook + hook*user	14	479.11	1.94	0.21
			base + hook + hook*leader	15	480.63	3.46	0.10
			base + hook + hook*taxa	15	481.14	3.97	0.07
			base + hook + hook*user + hook*leader	16	482.54	5.37	0.04
			base + hook + hook*taxa + hook*user	16	483.16	5.99	0.03
			base + hook + hook*taxa + hook*leader	17	485.11	7.94	0.01
			base + hook + hook*taxa + hook*leader + hook*taxa*leader	21	493.60	16.43	0.00
			base	12	501.35	24.18	0.00

charter trips. This trend was most pronounced on charter trips for all leader types (Fig. 6). The exception was a slightly greater hook-up rate for yellowfin tuna on circle hooks than on J hooks when fishing fluorocarbon leaders on recreational trips. For the taxa analysis, trends in model fitting to proportional hook-up data were similar to three species (Table 4; Fig. 7); hook was a main effect in the best fitting model and it was a main effect and interaction term in models receiving lesser support. The base model received no support (Table 4). The addition of mackerel data on recreational trips strengthened the trend of greater effectiveness of J hooks in hooking up these taxa on wire, the directed leader type for that group (Fig. 7).

The third mechanism contributing to catch was retention. Hook type did not appear to have a pronounced effect on proportion of fish retained (Fig. 8). For models fitted to species data, the base model received majority support (Table 5). A base model with a hook effect was the only other model receiving support, but it was minor. The proportion retained on circle hooks generally equaled (dolphinfish and yellowfin tuna) or slightly exceeded (wahoo) those retained on J hooks on directed leader types (Fig. 8). Proportional retention data for the taxa also showed that retention was high, with little to no difference between hook types (Table 5; Fig. 9). The base model received majority support and the base model with hook as a main effect received less support. Two other models that received minor support had hook-species and hook-user interactions (Table 5).

Estimates of effect size on catch rates determined from model-averaged predictions showed that J hooks were more effective than circle hooks. This trend held across the species and taxa levels. For the three species, mean predicted effect size (± standard deviation [SD]) for dolphinfish, yellowfin tuna, and wahoo on directed leader types was 0.60 (0.05), 0.60 (0.07), and 0.65 (0.09), respectively (Fig. 10), meaning that circle hooks were roughly 60% as effective as J hooks. For the taxa groups, mean predicted effect size (±SD) for dolphinfish, tunas, and mackerels was 0.62 (0.05), 0.62 (0.06), and 0.67 (0.08), respectively (Fig. 10).

There were no significant between-hook differences in the distribution of lengths for dolphinfish (χ^2=0.973, P=0.324), yellowfin tuna (χ^2=0.003, P=0.958), or wahoo (χ^2=0.068, P=0.795). Thus, hook type was not size selective within a species.

The effect of hook type on deep hooking was species dependent. Rates of deep hooking were significantly less for dolphinfish caught on circle hooks than J hooks (Table 6). However, there was no effect of hook type on proportion of deep-hooked wahoo or blackfin tuna. Rates

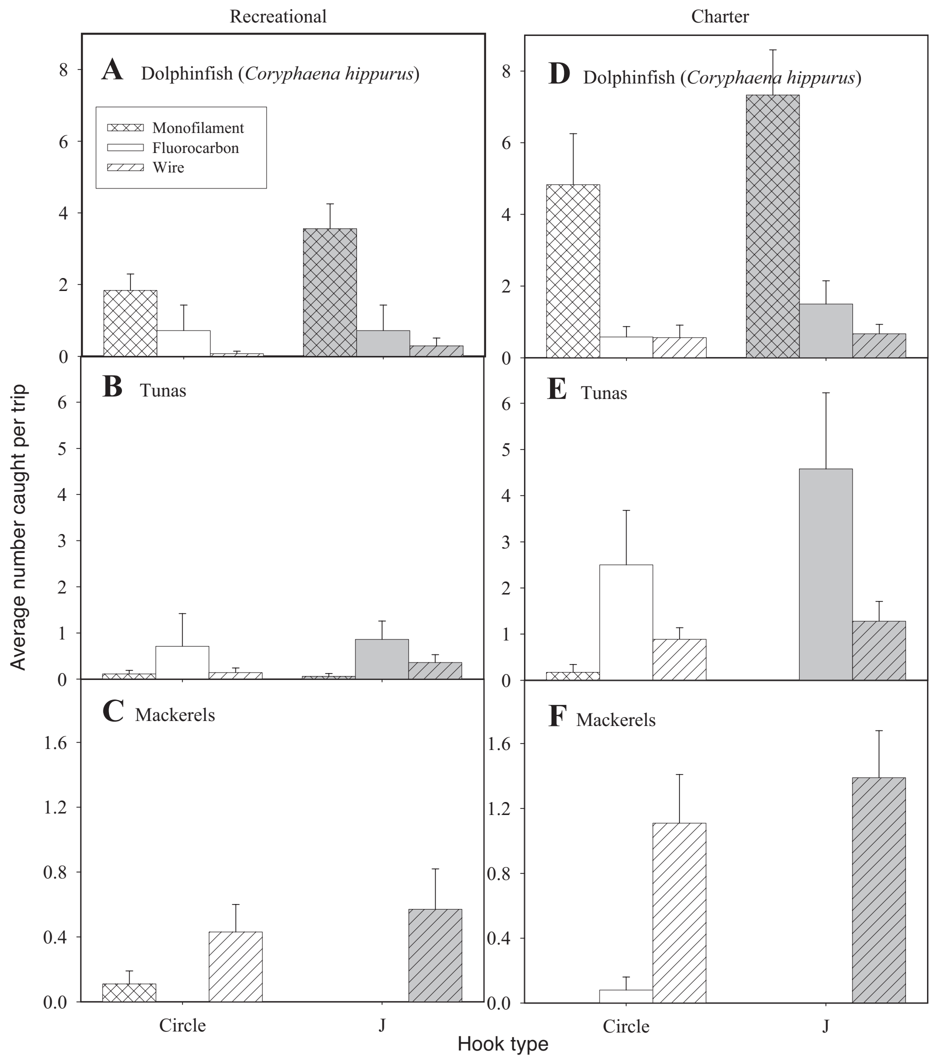

Figure 3

Plots of the average catch per trip (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for each group are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**], and charter [right column, panels **D–F**]), and taxa (dolphinfish *Coryphaena hippurus* [A, D], tunas [B, E], and mackerels [C, F]). The tuna group included yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus*), skipjack tuna (*Euthynnus pelamis*), and false albacore (*Euthynnus alletteratus)*. The mackerel group included wahoo (*Acanthocybium solandri*), king mackerel (*Scomberomorus cavalla*), and Spanish mackerel (*Scomberomorus maculatus*). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+taxon+user-group+leader-type combination indicates no catch.

of deep hooking were 0% for both circle and J hooks that caught yellowfin tuna.

Discussion

There is increased interest in requiring circle hooks in the recreational bluewater troll fishery in the United States. This is largely due to studies finding that circle hooks maintain catch rates but reduce rates of deep hooking compared with J hooks in billfishes (see Serafy et al., 2009, for review). In contrast, we found for non-billfishes that observed catch rates were reduced with circle hooks under that for J hooks in the charter group; similar findings were found in the recreational group for dolphinfish. Predictions of relative catch (through effect

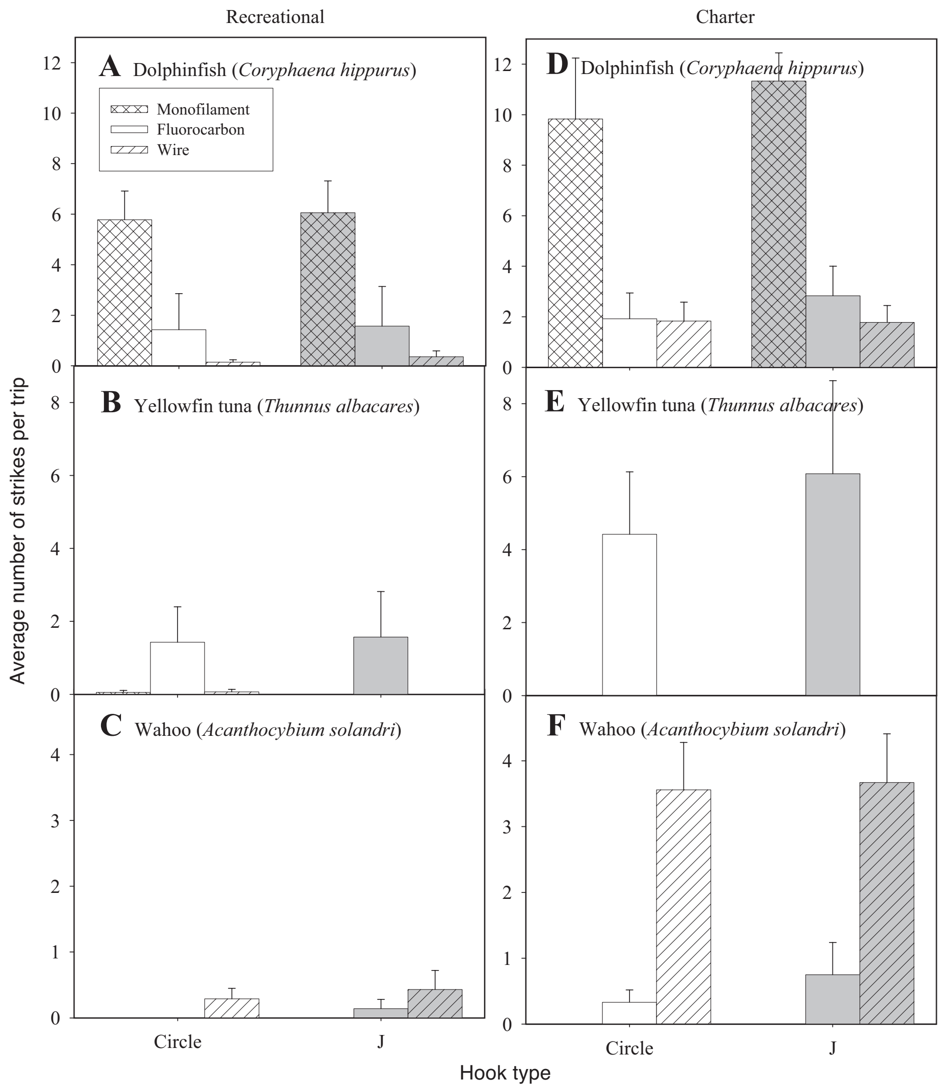

Figure 4

Plots of the average number of strikes per trip (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for plots includes strikes from unidentified fish later apportioned to species that could be identified. Data for each species are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **D–F**]) and species (dolphinfish [*Coryphaena hippurus*] [A, D], yellowfin tuna [*Thunnus albacares*] [B, E], and wahoo [*Acanthocybium solandri*] [C, F]). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+species+user-group+leader-type combination indicates no catch.

size calculations) indicate that fishermen can expect 65% greater catches of the three species or taxa groups on J hooks than on circle hooks. The similar findings between the species and taxa analyses indicate that morphological features of fish, attack styles, and hook effectiveness are consistent among the species of the tuna group and among the species of the mackerel group. Additionally, the similar results when smaller tunas and mackerels were included in the taxa analysis indicate that the ineffectiveness of circle hooks compared with J hooks is not size dependent within the range of fish sizes in our study.

The similarities between our findings and prior hook comparisons of hooks on longlines depend on the species being considered. In a Brazilian longline fishery, Sales et al. (2010) found a similar trend in dolphinfish catches to that found in our study (lower catches on circle hooks than on J hooks) but significantly more tunas caught on circle hooks than on J hooks. The increased catch

Table 3

Candidate models fitted to strike data for three species (dolphinfish [*Coryphaena hippurus*], yellowfin tuna [*Thunnus albacares*], and wahoo [*Acanthocybium solandri*]), and taxa (dolphinfish, tunas, and mackerels) when trolling circle and J hooks in Gulf Stream waters off North Carolina. Quasi-Akaike information criterion (QAIC) was used to evaluate model performance, with the lowest value indicating the most parsimonious model. Categorical predictor variables included hook type (hook), leader type (leader), species or taxa, and user group (user). Wave height was used as a continuous predictor variable. *K*=number of parameters for each model; *w*=Akaike weight. Base models included all predictor variables with exception of hook and any hook interactions; see *Methods* section for a full description of base models. ΔQAIC values ~<4 were considered models with reasonable support.

Interaction	Data type	Distribution	Model	*K*	QAIC	ΔQAIC	*w*
Strike: species	Count	Poisson	base + hook	15	979.96	0.00	0.36
			base	14	980.17	0.21	0.33
			base + hook + hook*user	16	981.89	1.93	0.14
			base + hook + hook*leader	17	983.42	3.46	0.06
			base + hook + hook*species	17	983.81	3.86	0.05
			base + hook + hook*user + hook*leader	18	985.40	5.44	0.02
			base + hook + hook*species + hook*user	18	985.75	5.79	0.02
			base + hook + hook*species + hook*leader	19	987.85	7.89	0.01
			base + hook + hook*species + hook*leader + hook*species*leader	23	996.39	16.43	0.00
B. Strike: taxa	Count	Poisson	base + hook	15	1050.57	0.00	0.40
			base	14	1051.09	0.52	0.31
			base + hook + hook*user	16	1052.66	2.08	0.14
			base + hook + hook*taxa	17	1054.54	3.97	0.05
			base + hook + hook*leader	17	1054.56	3.99	0.05
			base + hook + hook*taxa + hook*user	18	1056.59	6.01	0.02
			base + hook + hook*user + hook*leader	18	1056.64	6.07	0.02
			base + hook + hook*taxa + hook*leader	19	1058.92	8.34	0.01
			base + hook + hook*taxa + hook*leader + hook*taxa*leader	23	1067.40	16.83	0.00

rate of tunas on circle hooks over that for J hooks has been observed in other longline studies (Falterman and Graves, 2002). It is unclear what the mechanism is that leads to higher tuna catches on longline circle hooks, but lower tuna catches on trolled dead baits rigged with circle hooks; it is likely that tuna ingested the bait and hook more deeply in comparison to the actively trolled bait in our study. Actively trolling hooks (versus passive fishing on a longline) may be the mechanism contributing to these hook-type differences.

Most comparative studies of hooks in the dead bait troll fishery have been designed to estimate catch-and-release mortality in billfishes (Prince et al., 2002; Horodysky and Graves, 2005; Graves and Horodysky, 2010). The species that we examined in this study are not generally released; therefore, our focus was on the influence of hook type on catch rates and the potential mechanisms responsible for similarities or differences in catch by hook type, rather than on postrelease mortality. This was our focus because many charter boat captains suspect that circle hooks negatively impact catches of dolphinfish, tunas, and mackerels in the North Carolina dead-bait troll fishery. Our results confirm this suspicion. Model-averaged estimates suggest a strong negative effect of hook type on catch rates for all three species; however, examination of the raw data for individual species suggests that the effect of hook type on wahoo catch may be minor. Future studies with increased sample sizes would help to refine estimates of species by hook-type interactions, providing greater resolution of the importance and magnitude of hook effects for individual species. Thus, this is the first study to find that catch rates in a dead bait troll fishery can be negatively impacted by circle hooks. Horodysky and Graves (2005) and Graves and Horodysky (2010) did not provide comparisons of catch data between circle hooks and J hooks in their hook comparative studies on billfish.

Differences in strike, hook-up, and retention rates between hook types all have the potential to contribute to differences in catch rates. There was little evidence for a hook effect on strike rate; therefore, J and circle hook rigged baits were equally attractive to these three fish groups. Other studies that have compared hook types in the dead bait troll fishery have not reported data on strike rate by hook type; we recommend that this information be collected so that the specific mechanisms responsible for potential differences in catch rate can be determined.

The greater effectiveness of J hooks at hooking fish once they struck generally held across the three species and dolphinfish and the two taxa groups. Circle hooks

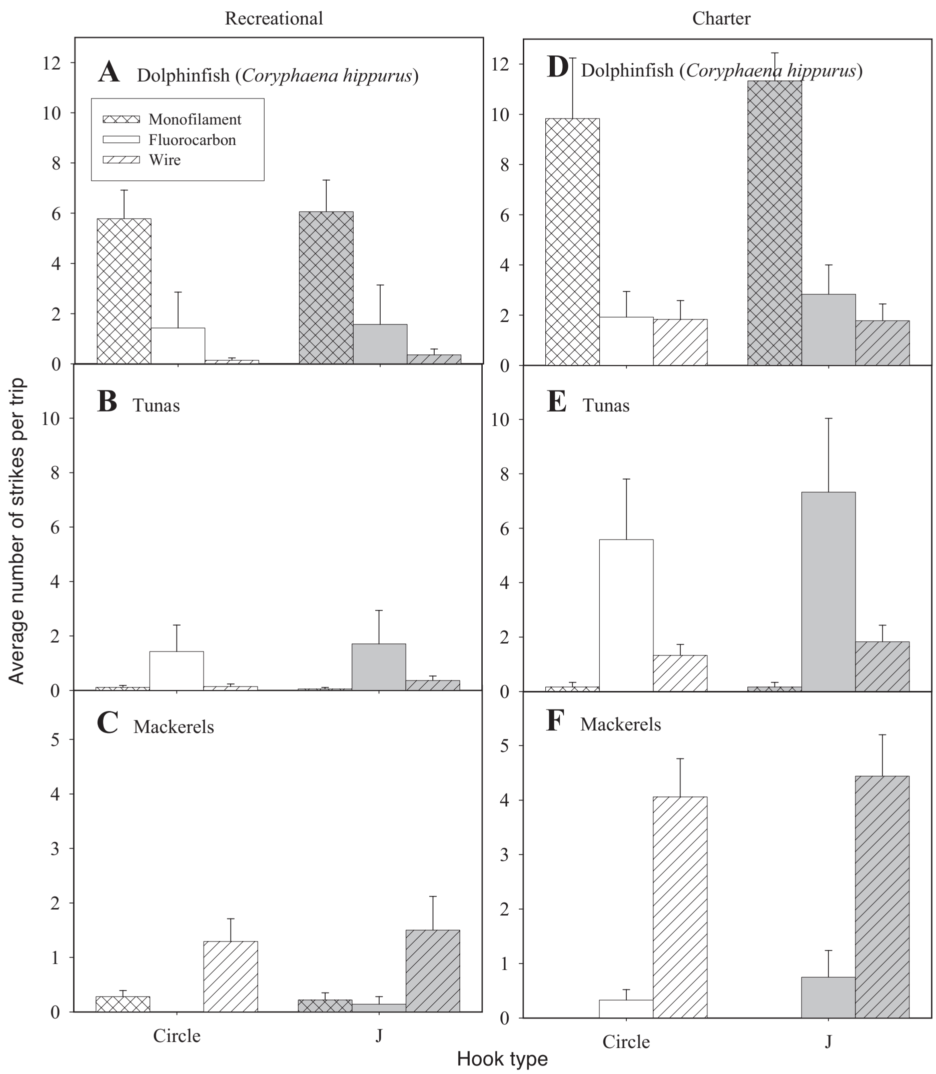

Figure 5

Plots of the average number of strikes per trip (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for plots include strikes from unidentified fish later apportioned to species that could be identified. Data for each group are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **D–F**]) and taxa (dolphinfish [*Coryphaena hippurus*] [A, D], tunas [B, E], and mackerels [C, F]). The tuna group included yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus*), skipjack tuna (*Euthynnus pelamis*), and false albacore (*Euthynnus alletteratus*). The mackerel group included wahoo (*Acanthocybium solandri*), king mackerel (*Scomberomorus cavalla*), and Spanish mackerel (*Scomberomorus maculatus*). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+taxon+user-group+leader-type combination indicates no catch.

are designed to hook fish if the hook rounds a corner within the jaw area. In theory, this would be most common for fish that turn their mouth opening away from the direction of the fishing line. However, if a fish is not seen during a strike, it is difficult to know when to reel the line tight (i.e., when the fish has turned). Our workshop panel (see *Methods* section) argued for a drop back for dolphinfish because this species is known to swim with the bait in their mouth in the direction that the line is trolled. The drop back for dolphinfish was done to allow enough time for the dolphinfish to turn. Even with these efforts, hook-up rates of dolphinfish were lower with circle hooks than J hooks for both user groups. Prince et al. (2002) found that hook-up

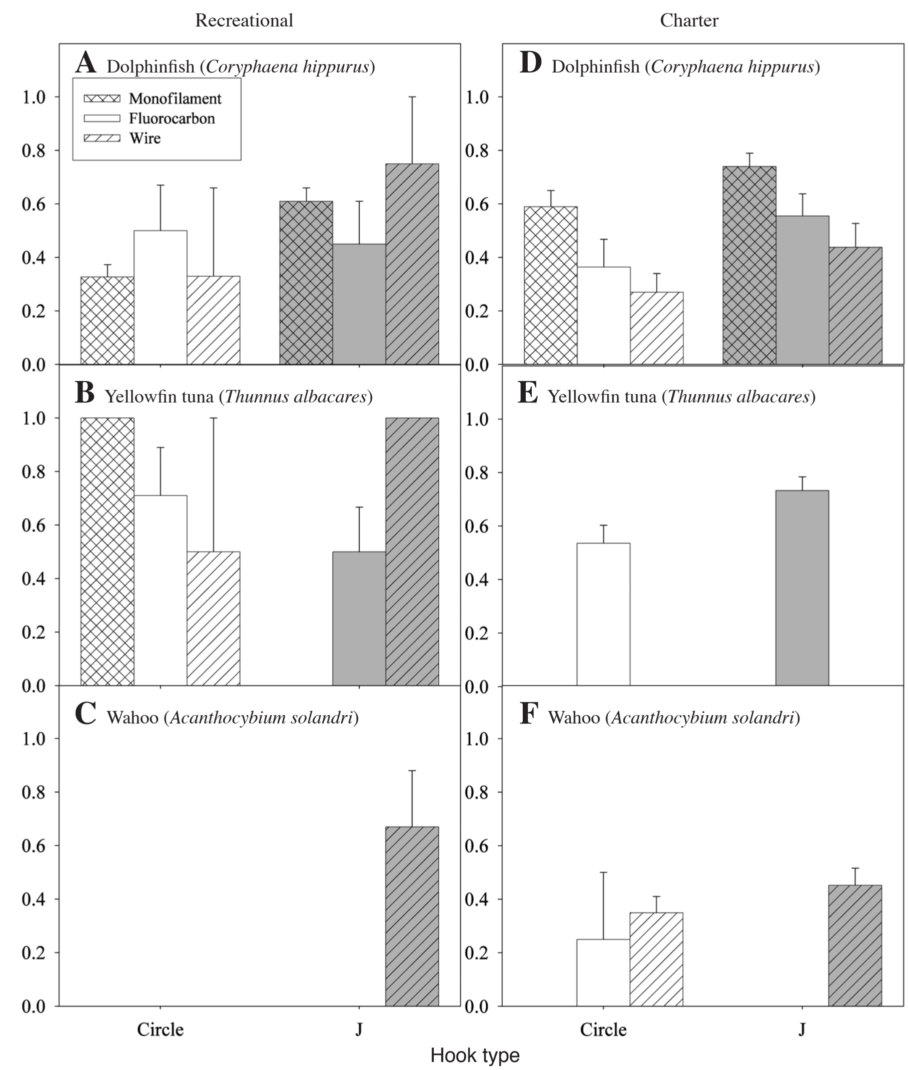

Figure 6

Plots of the average proportion of fish that hooked up (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for plots includes hook-ups from unidentified fish later apportioned to species that could be identified. Data for each species are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **E–F**]) and species (dolphinfish [*Coryphaena hippurus*] [A, D], yellowfin tuna [*Thunnus albacares*] [B, E], and wahoo [*Acanthocybium solandri*] [C, F]). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+species+user-group+leader-type combination indicates no catch.

rate on circle hooks was significantly higher than J hooks in a dead bait troll fishery for sailfish. The ability for the angler to visually see the fish with the bait in its mouth may allow for higher hook-ups on circle hooks in that fishery. In contrast, fishing for yellowfin tuna and wahoo involved using a heavy drag because the fish are aggressive and generally hook themselves upon striking (see Graves and Horodysky [2010] for a similar description and approach when targeting blue marlin). Theoretically, the circle hook should work in this heavy-drag situation only if the fish's mouth is at an angle to the direction of the line when the bait is taken into the mouth. Hook-up rates for yellowfin tuna and wahoo were slightly higher on J hooks on charter trips (for which we had the most data); this finding may be a result of some strikes on circle hooks where the mouth opening faced the direction that the bait was being trolled or because of bait rigging (see below). Graves

Table 4

Candidate models fitted to hook-up data for three species (dolphinfish [*Coryphaena hippurus*], yellowfin tuna [*Thunnus albacares*], and wahoo [*Acanthocybium solandri*]), and taxa (dolphinfish, tunas, and mackerels) when trolling circle and J hooks in Gulf Stream waters off North Carolina. Quasi-Akaike information criterion (QAIC) was used to evaluate model performance, with the lowest value indicating the most parsimonious model. Categorical predictor variables included hook type (hook), leader type (leader), species or taxa, and user group (user). Wave height was used as a continuous predictor variable. K=number of parameters for each model; w=Akaike weight. Base models included all predictor variables with exception of hook and any hook interactions; see *Methods* section for a full description of base models. ΔQAIC values ~<4 were considered models with reasonable support.

Interaction	Data type	Distribution	Model	K	QAIC	ΔQAIC	w
Hook-up: species	Proportion	Binomial	base + hook	11	–1159.03	0.00	0.38
			base + hook + hook*user	12	–1158.16	0.88	0.25
			base + hook + hook*species	13	–1156.75	2.29	0.12
			base + hook + hook*leader	13	–1156.53	2.51	0.11
			base + hook + hook*species + hook*user	14	–1155.07	3.96	0.05
			base + hook + hook*user + hook*leader	14	–1154.81	4.23	0.05
			base + hook + hook*species + hook*leader	15	–1154.75	4.28	0.04
			base + hook + hook*species + hook*leader + species*leader + hook*species*leader	23	–1148.53	10.51	0.00
			base	10	–1134.22	24.81	0.00
Hook–up: taxa	Proportion	Binomial	base + hook	11	–1393.91	0.00	0.40
			base + hook + hook*taxa	13	–1392.58	1.33	0.21
			base + hook + hook*user	12	–1392.17	1.74	0.17
			base + hook + hook*leader	13	–1390.90	3.00	0.09
			base + hook + hook*taxa + hook*user	14	–1390.48	3.43	0.07
			base + hook + hook*user + hook*leader	14	–1388.80	5.11	0.03
			base + hook + hook*taxa + hook*leader	15	–1388.72	5.19	0.03
			base + hook + hook*taxa + hook*leader + taxa*leader + hook*taxa*leader	23	–1385.27	8.64	0.01
			base	10	–1368.17	25.74	0.00

and Horodysky (2010) did not report hook-up percentage data for blue marlin and therefore it is unknown what hook-up rates would be for this aggressive feeder that is hooked upon strike.

One rigging tactic when trolling is to rig the circle hook so that it is completely external to the bony or fleshy portions of the bait to maximize the exposed gap width (e.g., the hook is placed on top of the bait's head; Prince et al., 2002). This placement is thought to work best for "dropping back" to fish because the fish have enough time to swallow the bait and the hook (dolphinfish and billfish trolling) and turn their body, while the exposed gap width of the circle hook is maximized. We did not employ the external rigging technique on days when yellowfin tuna or wahoo were targeted. Hooks were rigged internally for these two species because these species hook themselves upon striking; drop-backs are not typically required by charter or recreational fishers targeting these species. An additional reason for embedding hooks in baits was so that we could fish "combo" baits (lure and natural bait combinations) because colored lures (skirts) elicit more strikes than plain ballyhoo on most days for yellowfin tuna and wahoo. The cooperating mates on charter trips embedded the hook as close to the tail as possible without compromising the swimming action of the bait. Using larger circle hooks would have increased the gap width between the point and the point shank, potentially making hook-ups more likely, but this change could have compromised the strike rate by making the hook more visible to the fish or causing the bait to wash out faster.

There was little to no hook effect at the proportional retention level (caught once hooked) for dolphinfish, yellowfin tuna, and tunas, although there was increased retention of wahoo and mackerels on circle hooks and yellowfin tuna on circle hooks in the recreational fishery. The latter result is consistent with the findings of Prince et al. (2002) when trolling dead baits with circle and J hooks for sailfish. The increased retention on circle hooks relative to J hooks has been used as a selling point for circle hooks, but we did not find this result for the majority of species that we caught.

The procedure for assigning interactions with unidentified fish to a particular species is not ideal. For instance, if individuals of one species generate behavioral cues or are landed more readily than individuals for another species, species assignments may be biased toward more readily identified fish. In general, this approach decreased our ability to detect species effects on landing probabilities and hookup rates. However, we expected the reduction in statistical power to be relatively small and to affect only inferences about

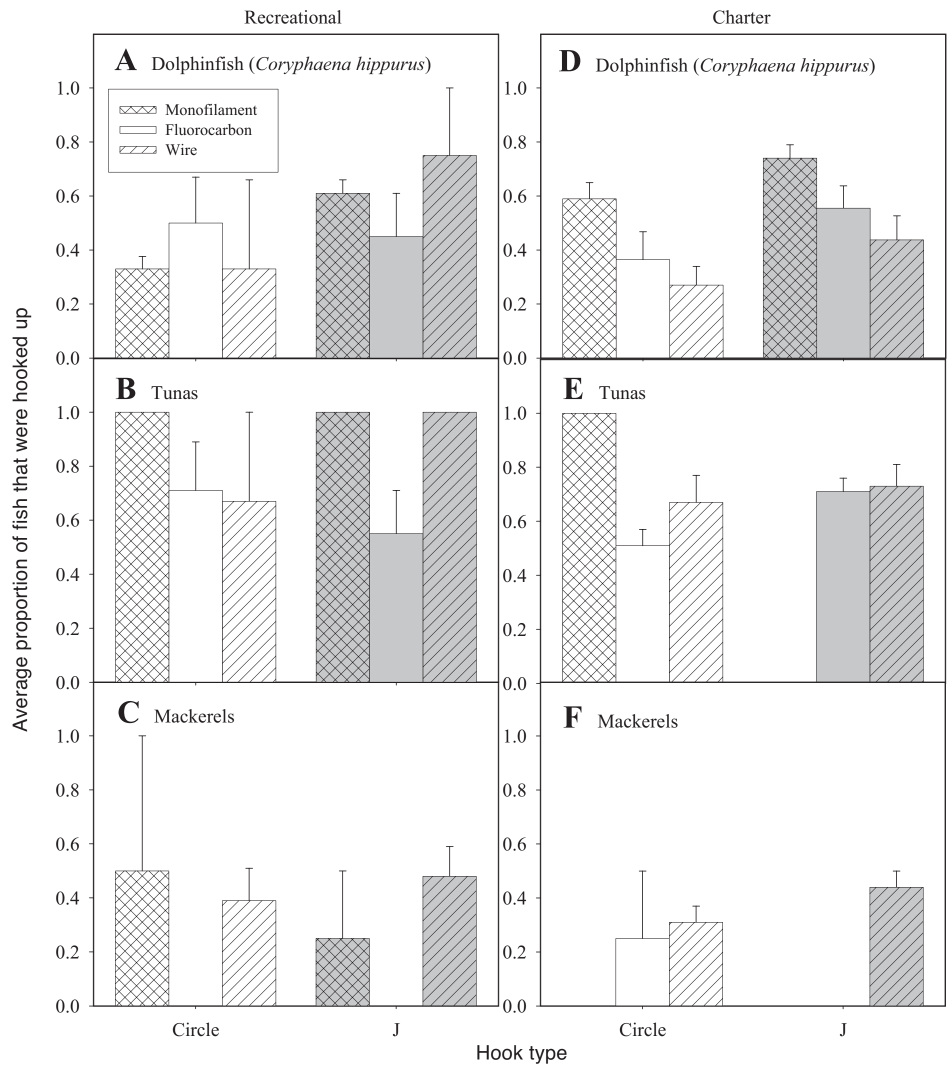

Figure 7

Plots of the average proportion of fish that hooked up (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for plots includes hook-ups from unidentified fish later apportioned to species that could be identified. Data for each group are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **E–F**]) and taxa (dolphinfish [*Coryphaena hippurus*] [A, D], tunas [B, E], and mackerels [C, F]). The tuna group included yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus*), skipjack tuna (*Euthynnus pelamis*), and false albacore (*Euthynnus alletteratus)*. The mackerel group included wahoo (*Acanthocybium solandri*), king mackerel (*Scomberomorus cavalla*), and Spanish mackerel (*Scomberomorus maculatus*). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+taxon+user-group+leader-type combination indicates no catch.

species-hook interactions; main effects for hook type remained unbiased.

If fishermen are interested in releasing dolphinfish, our results provide evidence that released fish are not hooked as deeply and thus have a higher likelihood of survival if circle hooks are used. The drop-back technique that we commonly used for dolphinfish likely led to a higher percentage of dolphinfish becoming deep hooked with J hooks over that for the tuna and mackerel taxa groups. The reduction in gut hooking with circle hooks has been found in most other studies comparing circle and J hooks (Cooke and Suski, 2004). Managers should factor in the high rate of deep hooking for J-hooked dolphinfish as they imple-

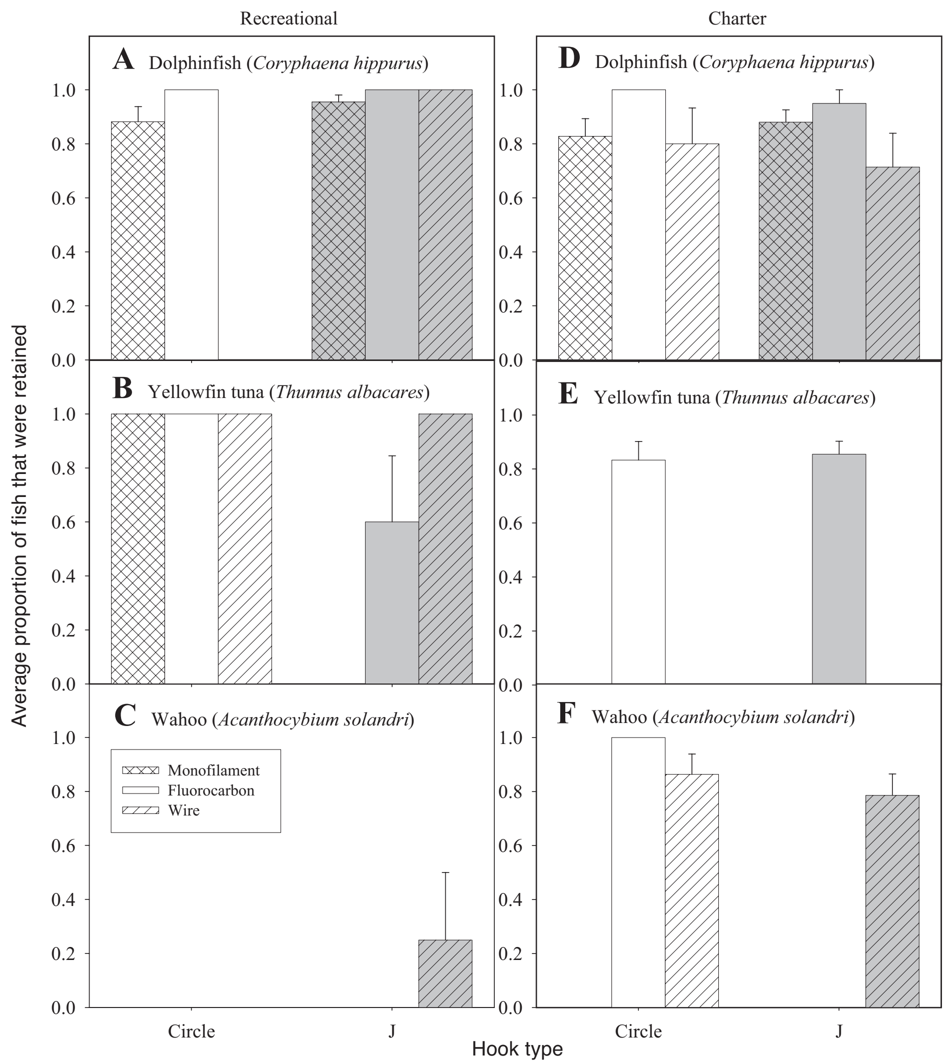

Figure 8

Plots of the average proportion of fish retained (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for each species are from both directed and non-directed trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **D–F**]) and species (dolphinfish *Coryphaena hippurus* [A, D], yellowfin tuna [*Thunnus albacares*] [B, E], and wahoo [*Acanthocybium solandri*] [C, F]). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+species+user-group+leader-type combination indicates no catch.

ment new minimum size regulations for this species in the U.S. South Atlantic (SAFMC, 2011). However, managers should also consider that there can be a trade-off when using circle hooks. Although rates of deep hooking are relatively low on circle hooks, handling time and air exposure are increased while dislodging them from captured fish owing to their inherently deeper bend than J hooks (Cooke and Suski, 2004; senior author, personal observ.). Along with outreach efforts to encourage the use of circle hooks where appropriate, instructions should be available on how to quickly remove the hooks with little injury to the fish.

Circle hooks remain vaguely defined. The federal definition of a circle hook (Federal Register, 2006) is somewhat arbitrary. Numerous circle hooks may meet the federal specifications, yet may not simultaneously reduce deep hooking in billfishes and maintain catch rates of non-billfishes. For example, some manufacturers advertise circle hooks with parallel or nearly parallel point shanks and hook shanks (like a J hook), but which simply have the tip of the point bent 90°

Table 5

Candidate models fitted to retention data for three species (dolphinfish [*Coryphaena hippurus*], yellowfin tuna [*Thunnus albacares*], and wahoo [*Acanthocybium solandri*]), and taxa (dolphinfish, tunas, and mackerels) when trolling circle and J hooks in Gulf Stream waters off North Carolina. Quasi-Akaike information criterion (QAIC) was used to evaluate model performance, with the lowest value indicating the most parsimonious model. Categorical predictor variables included hook type (hook), leader type (leader), species or taxa, and user group (user). Wave height was used as a continuous predictor variable. K=number of parameters for each model; w=Akaike weight. Base models included all predictor variables with exception of hook and any hook interactions; see *Methods* section for a full description of base models. ΔQAIC values ~<4 were considered models with reasonable support.

Interaction	Data type	Distribution	Model	K	QAIC	ΔQAIC	w
Retention: species	Proportion	Binomial	base	10	–876.22	0.00	0.63
			base + hook	11	–874.19	2.02	0.23
			base + hook + hook*leader	13	–871.13	5.09	0.05
			base + hook + hook*species	13	–870.76	5.46	0.04
			base + hook + hook*species + hook*user	14	–869.35	6.87	0.02
			base + hook + hook*user + hook*leader	14	–869.16	7.05	0.02
			base + hook + hook*species + hook*leader	15	–867.10	9.12	0.01
			base + hook + hook*user	12	–857.77	18.45	0.00
			base + hook + hook*species + hook*leader + species + leader hook*species*leader	23	–854.71	21.51	0.00
Retention: Taxa	Proportion	Binomial	base	12	–1112.66	0.00	0.53
			base + hook	13	–1110.55	2.11	0.19
			base + hook + hook*species	15	–1108.74	3.92	0.08
			base + hook + hook*user	14	–1108.74	3.93	0.08
			base + hook + hook*leader	15	–1108.54	4.12	0.07
			base + hook + hook*species + hook*user	16	–1106.71	5.95	0.03
			base + hook + hook*user + hook*leader	16	–1106.40	6.26	0.02
			base + hook + hook*species + hook*leader	17	–1104.87	7.79	0.01
			base + hook + hook*species + hook*leader + hook*species*leader	23	–1092.10	20.56	0.00

Table 6

Percentage of fish caught in two anatomical locations (jaw vs. "deep" [body, gill, gut, eye]) with trolled circle and J hooks. The χ^2 test statistic and P-value from each test of independence comparing hooking locations between hook types are presented for each species. A χ^2 test was not conducted for king mackerel because of small sample size.

	Circle hook		J hook			
Species	Jaw	Deep	Jaw	Deep	χ^2	P
Dolphinfish (*Coryphaena hippurus*)	98.5	1.5	61.3	38.7	31.35	<0.001
Yellowfin tuna (*Thunnus albacares*)	100	0	100	0	—	—
Wahoo (*Acanthocybium solandri*)	100	0	91.3	8.7	1.82	0.177
Blackfin tuna (*Thunnus atlanticus)*	100	0	92.6	7.4	1.13	0.287
King mackerel (*Scomberomorus cavalla*)	100	0	66.7	33.3		

toward the shank. Having discussed the structure of the hooks with captains, Smith (2006) postulated that a greater turn in the point shank (a point shank that turns back towards the hook shank by ≥33°) reduces the chances for deep hooking in billfishes. This outcome has yet to be determined with experimental fishing and would be a useful area of future research. We measured the angle between the point shank and hook shank to be roughly 25 degrees for the circle hooks we used (regardless of the size). Compared with the circle hook styles we tested, other circle hooks with different point shank angles that still satisfy federal requirements may have performed better at catching non-billfish species.

The fishing tackle industry and charter boat operators continually adapt gear and techniques to increase

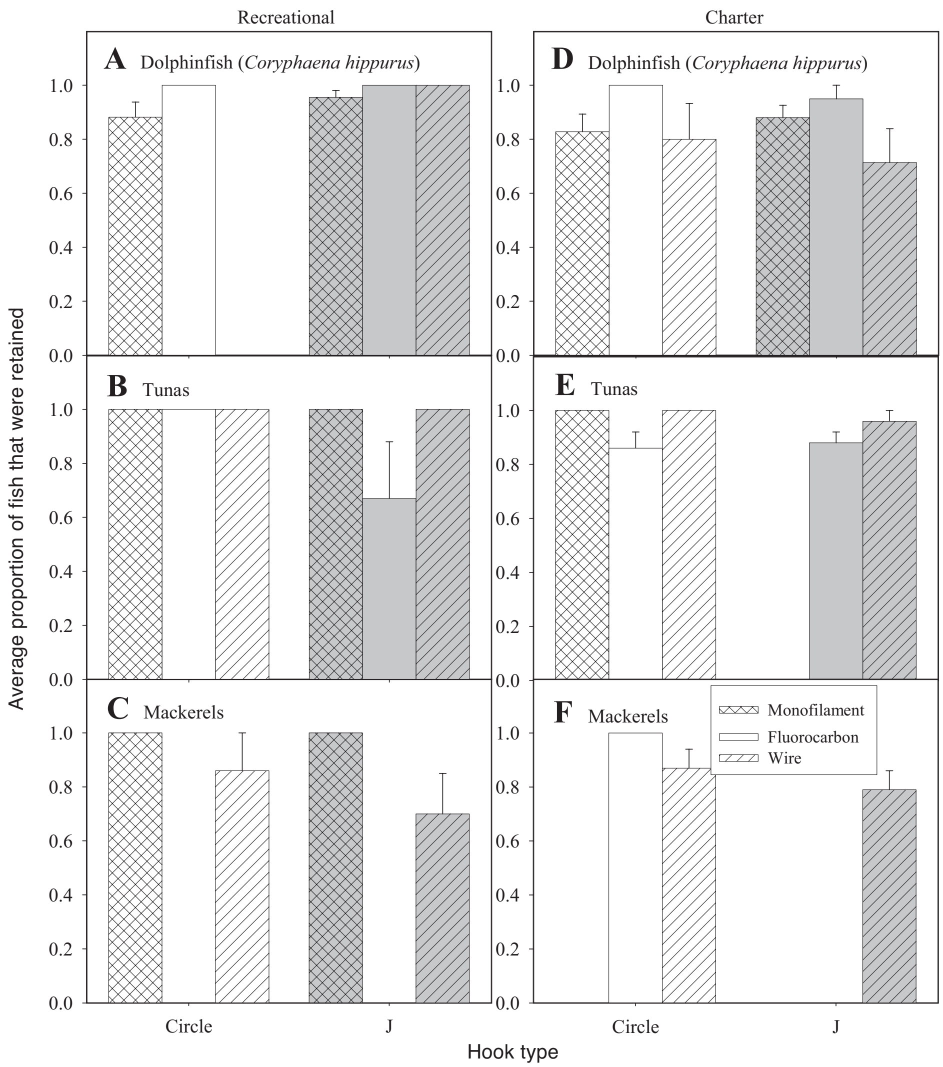

Figure 9

Plots of the average proportion of fish retained (±standard error) on circle hooks (open bars) and J hooks (gray bars). Data for each group are from both directed and nondirected trips for that species. Plots are broken down by user group (recreational [left column, panels **A–C**] and charter [right column, panels **D–F**]) and taxa (dolphinfish *Coryphaena hippurus* [A, D], tunas [B, E], and mackerels [C, F]). The tuna group included yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus*), skipjack tuna (*Euthynnus pelamis*), and false albacore (*Euthynnus alletteratus).* The mackerel group included wahoo (*Acanthocybium solandri*), king mackerel (*Scomberomorus cavalla*), and Spanish mackerel (*Scomberomorus maculatus*). The legend denoting fill pattern for each leader type applies to all panels. No bar for a particular hook-type+taxon+user-group+leader-type combination indicates no catch.

catch efficiency. There are likely untested techniques that allow fishermen to catch non-billfish with circle hooks more efficiently than we found in this study. Cooke and Suski (2004) report that the choice of circle hook size is an important consideration in order to maximize their effectiveness. Hook size seems to be an especially important consideration in a mixed-species and mixed-size fishery such as the one we examined. Hook choice (size and style) was a central topic in the workshop we convened; in targeting each of the main species (dolphinfish, yellowfin tuna, and wahoo), we selected hook sizes and styles recommended by experienced offshore fishermen.

It is likely that fishermen would be more inclined to experiment with circle hooks and novel rigging strategies if they knew there would be a pending requirement to use them outside of Atlantic billfish tournaments. Industry willingness to refine rigging techniques and fishing strategies in the face of future hook-type regulations could help increase experimentation with circle hooks, and thus catch rates of non-billfish species when trolling for them in this fishery. The workshop we convened generated many novel rigging and fishing techniques with circle hooks, only a fraction of which we used for the field experiment of this project.

We urge future studies to provide catch rates (numbers standardized to effort), strike, hook-up, and retention data for both hook types so that trade-offs between catch-and-release survival and catch rates can be evaluated. In addition, the terms used when discussing these variables should also be standardized. For example, the catch rate for trolled baits as defined by Serafy et al. (2009) equals a retention rate (caught if hooked), but a fisherman's interest lies in knowing how many fish will be caught per trip which is the product of number of strikes, proportion hooked, and proportion retained. Without knowledge of the first two variables, the third variable only provides information about a hook's effectiveness at retaining a fish on the line and not its overall effectiveness.

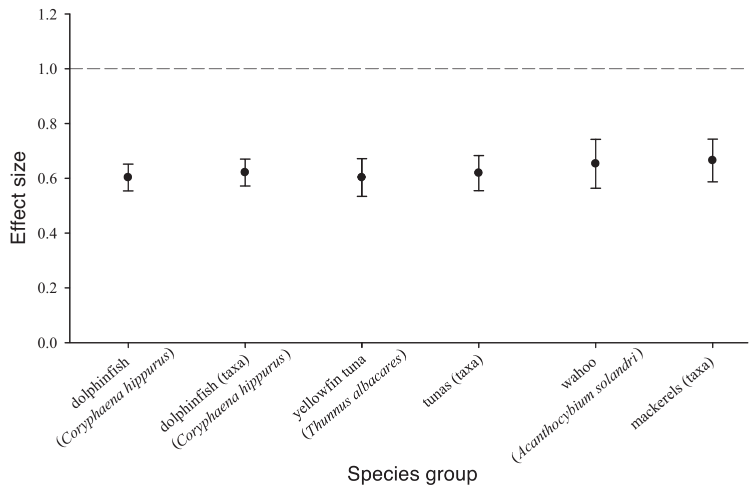

Figure 10

Mean predicted effect size (±standard deviation) of circle versus J hooks on catch rates by species or taxa group. Dolphinfish (*Coryphaena hippurus*) is listed twice because the predicted effect size changes slightly in comparisons with the "tunas" and "mackerels" taxa groups. An effect size greater than 1 indicates greater effectiveness of circle hooks than J hooks; the opposite is true for an effect size less than 1. An effect size equal to 1 (dashed line) indicates that the hook types are equally effective. The mean and variance of each effect size was calculated by using weighted model averages from each model with positive Akaike weight (w_i) at the catch level (see *Materials* section for details).

Conclusions

We examined three mechanisms that may have been responsible for the hook effect on catch rates. These were strike, hook-up, and retention. There was little to no hook effect at the strike and retention levels. However, the differences in catch rates we observed resulted from a lower hook-up rate on circle hooks compared with J hooks. This trend was generally consistent across analyses of data on three species and on three broader taxa.

It is unknown whether a requirement to troll exclusively circle hooks in the offshore fishery would have an economic impact on either the recreational or charter fisheries in this region. It is likely that circle hooks need to catch fish at rates near, equal to, or higher than J hooks to gain wider acceptance among offshore troll fishermen (Jordan, 1999). We hope that angler experimentation will lead to improvements in circle hook catch rates for non-billfish species caught during trolling operations.

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