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CAN CIRCLE HOOK OFFSET COMBINED WITH BAITING TECHNIQUE AFFECT CATCH AND BYCATCH IN PELAGIC LONGLINE FISHERIES?

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ABSTRACT

Circle hooks have become a standard requirement in many commercial longline fisheries in the United States, and are used increasingly worldwide. Circle hooks, when compared to J-hooks, are thought to reduce bycatch without significantly decreasing (and possibly increasing) catch of most target species. Circle hook offset and baiting technique are also thought to influence bycatch and mortality of species of concern, such as sea turtles and billfishes. We compared non-offset circle hooks to those with a 10° offset and single or threaded baiting techniques in the United States Atlantic and Gulf of Mexico pelagic longline fishery. Offset and/or baiting techniques were compared within sets targeting one of three species independently: swordfish, *Xiphias gladius* Linnaeus, 1758, yellowfin tuna, *Thunnus albacares* (Bonnaterre, 1788), and bigeye tuna, *Thunnus obesus* (Lowe, 1839). Most comparisons of catch and bycatch did not differ between gears or techniques. In swordfish-directed sets, we found a 46% decline in catch of Atlantic sailfish when using 18/0 non-offset circle hooks single baited with mackerel compared to 18/0 10° offset circle hooks with threaded mackerel. In yellowfin tuna sets, single baiting significantly decreased target catch by 22% and escolar catch by 28%, compared to threaded baiting. We detected no significant effect of any of the offset or baiting treatments on the bycatch of sea turtles and most other species of concern due to the rarity of capture events. We conclude, in part, that bycatch mitigation research in other fisheries with larger detrimental population level impacts to species of concern may potentially yield greater conservation benefits.

Circle hooks have become a standard requirement in many commercial pelagic longline fisheries in the United States to reduce bycatch, and increasingly are used worldwide. Species groups of bycatch concern in pelagic longline fisheries include sea turtles (Watson et al. 2005, Sales et al. 2010), billfishes (Kerstetter and Graves 2006a, Diaz 2008, Serafy et al. 2009), sharks (Kerstetter and Graves 2006b, Yokota et al. 2006), and marine mammals (Silva et al. 2002, Garrison 2007), as well as undersized swordfish in US pelagic longline fisheries. Circle hooks and J-hooks vary in shape, size, and offset (the angle of the point relative to the shank, see Prince et al. 2007). Despite this variation, when compared to J-hooks, circle hooks are thought to reduce bycatch of some species such as sea turtles (Watson et al. 2005, Piovano et al. 2009, Sales et al. 2010), increase post release survivorship of hooked fish (Bartholomew and Bohnsack 2005, Horodysky and Graves 2005, Serafy et al. 2009), and may increase (Woll et al. 2001, Gilman et al. 2007) or at least not significantly decrease the catch of most target species (Watson et al. 2005, Piovano et al. 2009, Foster et al. 2012). Billfishes in particular are thought to benefit from circle hook use because boatside mortality and severity of injuries are reduced (Serafy et al. 2009).

The degree of circle hook offset and baiting technique onto circle hooks are both thought to influence bycatch and post-release mortality of sea turtles (Gilman et al. 2006) and other species (Prince et al. 2002). Fishers appear to prefer offset circle hooks due to ease of baiting and perceived greater catch rates compared to non-offset circle hooks, and tend to use either a single baiting technique, where finfish bait is hooked once through both eyes, or a threaded baiting technique, where the hook is passed through the bait in two places, covering more of the hook. In a study of paired comparisons between offset and non-offset circle hooks in a pelagic longline fishery, Swimmer et al. (2010) found no effect on sea turtle bycatch or on the catch of other species. However, Epperly et al. (2012) found survival differences between non-offset and offset circle hooks.

We hypothesize that the greater the circle hook offset, the greater the probability of gut hooking and foul hooking in sea turtles because as offset increases, an offset circle hook may act more like a J-hook. We further hypothesize that the threaded baiting technique would capture more sea turtles by mouth or gut hooking than the single hooking technique because sea turtles may be more likely to ingest a hook with threaded bait, whereas with single hooked baits sea turtles could tear off some of the bait without getting a hook in their mouth (Gilman et al. 2006, Stokes et al. 2011).

Our objectives were to evaluate the pelagic longline bycatch reduction capability of non-offset circle hooks and single baiting techniques compared to 10° offset circle hooks and threaded baiting techniques. The study was conducted in the Gulf of Mexico and western North Atlantic coastal management areas of the US, for those vessels targeting swordfish, yellowfin tuna, and bigeye tuna (see Appendix 1 for species and authorities). We also examined the catch rates and boatside mortality of the five most commonly caught species in each study to evaluate the impact of the gear changes on target and other landed species.

Methods

Three independent studies in cooperation with industry were conducted in 2005 on pelagic longline vessels in the western North Atlantic and in the Gulf of Mexico (Fig. 1). We examined the impact of bycatch reduction technologies relative to existing gear on vessels targeting swordfish, yellowfin tuna, or bigeye tuna. The gear, baiting technique, and the regions fished varied by target species. We conducted each experiment during the 3-mo period that was anticipated to have the most interactions with the regional bycatch priority species for each of the target species. Each study examined two experimental treatments, paired within each set by alternating either hook offset, baiting technique, or hook offset combined with baiting technique (e.g., offset, no offset, offset). All branch lines or snaps were color coded to allow positive identification of hook type and baiting technique used. We did not expect color coding to impact our treatments because colors were far from the bait and, at least in sea turtles, bait color does not appear to impact bycatch (Swimmer et al. 2005).

All research sets used commercial longline gear configurations and fishing practices associated with the region and target species. All gear configurations were consistent within a set (see Table 1 for details). Branch lines were at least 110% of the float line length. Hook spacing was uniform within a set. All fish that could be legally landed were retained for sale by the vessel.

Swordfish.—We employed pelagic longline vessels to conduct sets targeting swordfish from May 15 to August 19, 2005, to evaluate bycatch reduction potential for 18/0 non-offset circle hooks (e.g., fig. 2 in Watson et al. 2005) with single hooked Boston mackerel, *Scomber*

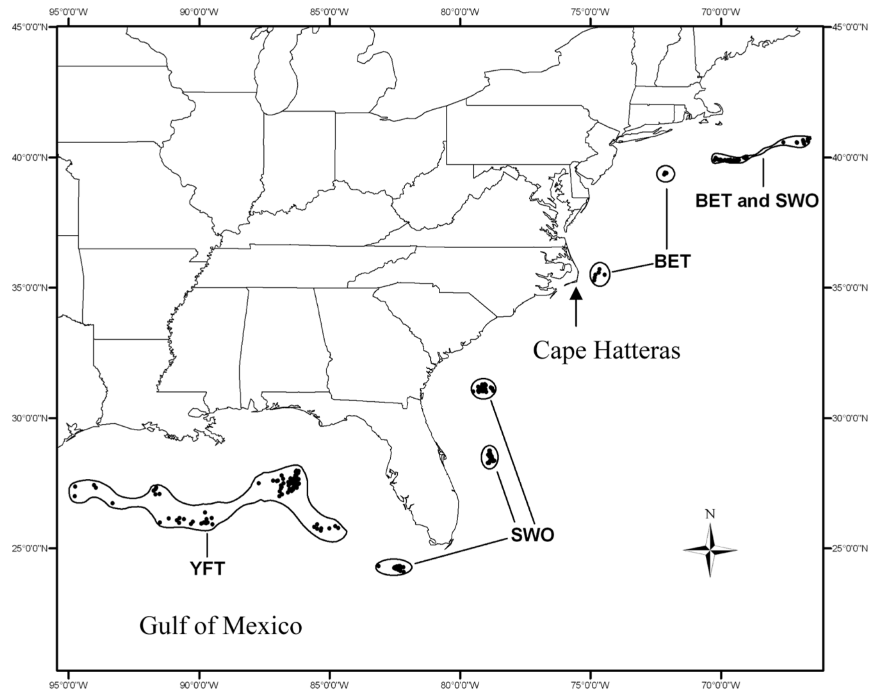

Figure 1. Map of the western North Atlantic off the coast of the United States showing the location of experimental sets by target (SWO = swordfish, YFT = yellowfin tuna, BET = bigeye tuna).

scombrus Linnaeus, 1758, bait (hereafter referred to as SWO-0-S) compared to 18/0 10° offset hooks (e.g., fig. 2 in Watson et al. 2005) with threaded Boston mackerel bait (hereafter referred to as SWO-10-T). Thus this experiment tested offset and baiting method effects in the swordfish fishery. All treatments used 150–500 g Boston mackerel as bait. In the single baiting technique the bait was hooked through both eyes (e.g., fig. 3A in Broadhurst and Hazin 2001) from either direction (for left and right handed baiters). In the threaded baiting technique, the bait was hooked through the side behind the dorsal fin (last 1/3 of tail), then reentered in the forward portion of the top side of the bait ending with the exposed hook coming out of the top side of the head just behind the eyes (e.g., fig. 3B in Broadhurst and Hazin 2001).

Yellowfin Tuna.—We employed pelagic longline vessels to conduct sets targeting yellowfin tuna in the Gulf of Mexico from April 17 to September 26, 2005, to evaluate bycatch reduction potential for 16/0 non-offset circle hooks with single hooked Spanish sardine baits (hereafter referred to as YFT-0-S) compared to 16/0 non-offset circle hooks with threaded Spanish sardine baits (hereafter referred to as YFT-0-T). This experiment tested for the baiting method effect in the yellowfin tuna fishery. Spanish sardine baits were standardized to 2.7–3.6 kg^{-1} (6–8 lb^{-1}). The single baiting technique hooked the bait through both eyes (e.g., fig. 3A in Broadhurst and Hazin 2001) from either direction (left and right handed baiters). The threaded baiting technique for this experiment used a hook that was tied such that the leader was in line with the hook shank, which entered through both eyes from either direction, then reentered through body of the bait.

Table 1. Details of fishing gear configurations by swordfish-, yellowfin tuna–, and bigeye tuna–targeted sets.

Target type	Region	Hooks between floats	Leader length (m)	Swivel distance above hook (m)	Drop distance (m)	Lightsticks
Swordfish	North of Cape Hatteras	5	4.6	4.6	3.7 or 9.1	Green on every leader
	South of Cape Hatteras	5	21.9	4.6	12.8 or 18.3	Green on every leader
	Gulf of Mexico	5	45.7	4.6	18.3	Green on every leader
Yellowfin tuna	Gulf of Mexico	5	64.0	9.1	21.9	None
Bigeye tuna	North of Cape Hatteras	5 or 7	4.6	4.6	3.7 or 9.1	Green on every hook

Bigeye Tuna.—We employed pelagic longline vessels to conduct sets targeting bigeye tuna north of Cape Hatteras from June 6 to August 19, 2005, to evaluate bycatch reduction potential for 18/0 non-offset circle hooks (e.g., fig. 2 in Watson et al. 2005) with whole squid bait (hereafter referred to as BET-0-Sq) compared to 18/0 10° offset circle hooks (e.g., fig. 2 in Watson et al. 2005) with whole squid bait (hereafter referred to as BET-10-Sq). Threaded squid bait was the same for both treatments, thus this experiment tested for the hook offset effect in the bigeye tuna fishery. All sets used 150–300 g *Illex* sp. squid placed on the hook through the tip of the mantle on the belly side (reverse side of tail flaps). The hook was inserted in the squid belly and pushed through to fully expose the hook point and barb to allow the monofilament tail holder to fit securely through the squid tail.

Statistical Analysis.—All experiments were designed as paired comparisons. Each set within each target experiment was treated as an independent experimental unit (e.g., each set by vessels targeting bigeye tuna was treated as an experimental unit). In most cases, we performed paired t-tests (e.g., Swimmer et al. 2010); when catch was small we employed the non-parametric Wilcoxon signed-rank test (in all analyses, significance was determined at $\alpha = 0.05$). In no case was significance determined without the paired t-test and the Wilcoxon signed-rank test both being in agreement. We also used the Cochran-Mantel-Haenszel test to determine differences in the counts of the number of dead and alive at boatside by species by set (Kerstetter and Graves 2006b). All statistical analyses were performed using R (v. 2.13.0, freeware. Available at: http://www.r-project.org via the Internet. Accessed 18 July, 2011). In most cases, where sample size was sufficient, we evaluated catch per unit effort (CPUE) and mortality. CPUE was calculated per set as the number of individuals captured per 1000 hooks by treatment. Percent mortality was calculated per set as the number of individuals observed dead at boatside divided by the total number of individuals captured in the set by treatment multiplied by 100. If no individuals were captured by either treatment in a set, then that set was excluded from analysis because there was no observed paired comparison.

Results

From all three experiments we observed a total of 203 pelagic longline sets and a total of 130,953 hooks (swordfish: 78 sets of 39,741 hooks; yellowfin tuna: 85 sets of 57,805 hooks; bigeye tuna: 40 sets of 33,407 hooks). The target species was the largest proportion of the catch in only one of the three experiments (Tables 2, 3, and 4). Swordfish made up the largest proportion of the catch (43%, Table 2) in the swordfish-targeted sets. In the yellowfin tuna–targeted sets, lancetfish, a bycatch species, was the largest proportion of the catch (34%, Table 3) and yellowfin tuna made up the second largest proportion of the catch (22%). In bigeye tuna–targeted sets, bigeye tuna made up a relatively small proportion of the catch (approximately 3.8%, Table 4), with swordfish comprising the largest proportion of the catch (28%, Table 4).

Swordfish.—We found a nearly 46% reduction in catch rates for Atlantic sailfish in swordfish-targeted sets, when using single hooking baiting on non-offset circle hooks (Table 5) accompanied by no significant decrease in boatside mortality. There were no other significant differences in catch rate or boatside mortality in any of the other species (Table 5). We also found no significant decrease in the catch rate of undersized swordfish (<120 cm from the tip of the lower jaw to tail fork) on SWO-0-S treatment ($t = 0.73$, df = 62, $P = 0.47$).

Table 2. Percent of total catch and number caught by experimental treatment from sets targeting swordfish (*Xiphias gladius*). A 10° offset 18/0 circle hook with threaded mackerel bait (SWO-10-T) was the control and the treatment was a non-offset 18/0 circle hook with single hooked mackerel bait (SWO-0-S). See Appendix 1 for species names.

Common name	Percent of catch	Control SWO-10-T	Treatment SW0-0-S	No data
Swordfish	43.49	598	574	4
Night shark	8.06	92	124	2
Requiem shark	7.21	100	91	4
Silky shark	5.84	72	86	
Dolphinfishes	5.81	74	83	
Atlantic sailfish	4.92	86	47	
Tiger shark	4.03	60	44	5
Escolar	3.70	47	53	
Barracudas	1.89	20	30	1
Shortfin mako	1.78	25	23	
Lancetfishes	1.52	21	20	
Blue marlin	1.11	13	17	
Yellowfin tuna	1.11	14	16	
Sandbar shark	1.07	12	17	
White marlin	1.07	16	12	1
Blue shark	0.81	11	11	
Bigeye thresher	0.78	8	11	2
Bigeye tuna	0.48	4	9	
Manta ray	0.48	6	7	
Dusky shark	0.41	5	6	
Oilfish	0.41	9	2	
Blackfin tuna	0.37	6	4	
Bluefin tuna	0.37	5	5	
Wahoo	0.37	3	7	
Bull shark	0.33	6	3	
Thresher shark	0.33	2	7	
Longfin mako	0.30	6	1	1
Oceanic whitetip shark	0.30	2	6	
Scalloped hammerhead shark	0.18		5	
Common thresher	0.15		4	
Hammerheads	0.15	1	3	
Leatherback sea turtle	0.15	1	3	
Nurse shark	0.15		4	
Snake mackerel	0.15	1	2	1
Sharks	0.11	1	1	1
Skates and rays	0.11	1	2	
Tunas	0.11	3		
Loggerhead sea turtle	0.07	1	1	
Porbeagle	0.07	1	1	
Roundscale spearfish	0.07	1	1	
Albacore tuna	0.04		1	
Greater Shearwater	0.04	1		
Pelagic stingray	0.04		1	
Skipjack	0.04		1	
Ocean sunfishes	0.04	1		

Table 3. Percent of total catch and number caught by experimental treatment from sets targeting yellowfin tuna (*Thunnus albacares*). Non-offset 16/0 circle hook with threaded sardine bait (YFT-0-T) was the control, and the treatment was a non-offset 16/0 circle hook with single hooked sardine bait (YFT-0-S). See Appendix 1 for species names.

Common name	Percent of catch	Control YFT-0-T	Treatment YFT-0-S	No data
Lancetfishes	34.85	372	424	4
Yellowfin tuna	22.20	283	224	18
Escolar	9.72	129	93	2
Swordfish	7.27	75	91	3
Blackfin tuna	5.74	70	61	3
Wahoo	4.12	54	40	1
Skipjack	2.71	29	33	1
Dolphinfishes	2.54	30	28	
White marlin	1.71	16	23	
Pelagic stingray	1.23	16	12	
Bluefin tuna	0.79	12	6	1
Blue marlin	0.70	6	10	
Pomfrets	0.70	11	5	
Billfishes	0.66	8	7	1
Skates and rays	0.57	7	6	
Barracudas	0.48	5	6	
Sandbar shark	0.48	8	3	
Tunas	0.48	8	3	1
Tiger shark	0.44	6	4	
Bigeye tuna	0.35	6	2	
Atlantic sailfish	0.31	2	5	1
Requiem shark	0.31	1	6	
Silky shark	0.31	3	4	
Leatherback sea turtle	0.22	4	1	2
Sharks	0.18	4		
Oilfish	0.13	2	1	
Opah	0.13		3	
Dusky shark	0.09		2	
Longfin mako	0.09	1	1	
Shortfin mako	0.09	2		
Spearfishes	0.09	1	1	
Bigeye thresher	0.04		1	
Common thresher	0.04	1		
Longbill spearfish	0.04		1	
Manta ray	0.04	1		1
Night shark	0.04	1		
Oceanic whitetip shark	0.04	1		
Puffers	0.04	1		
Thresher shark	0.04	1		

Table 4. Percent of total catch and number caught by experimental treatment from sets targeting bigeye tuna (*Thunnus obesus*). A 10° offset 18/0 circle hook with squid bait (BET-10-Sq) was the control, and the treatment was a non-offset 18/0 circle hook with squid bait (BET-0-Sq). See Appendix 1 for species names.

Common name	Percent of catch	Control BET-10-Sq	Treatment BET-0-Sq	No data
Swordfish	28.52	156	183	1
Yellowfin tuna	14.68	81	94	
Dolphinfishes	11.24	75	59	
Blue shark	8.81	50	53	2
Pelagic stingray	7.89	56	38	
Manta ray	4.95	28	20	11
Bigeye tuna	3.86	26	20	
Shortfin mako	3.27	21	18	
Bluefin tuna	2.85	12	21	1
Scalloped hammerhead shark	2.60	18	13	
Tiger shark	2.52	14	16	
Lancetfishes	2.27	14	13	
White marlin	1.59	8	11	
Loggerhead sea turtle	0.50	2	4	
Albacore tuna	0.42	2	3	
Leatherback sea turtle	0.42	2	1	2
Night shark	0.34	1	3	
Roundscale spearfish	0.34	2	2	
Tunas	0.34	3	1	
Atlantic sailfish	0.25	3		
Bigeye thresher	0.25	1	2	
Pilot whale	0.25	1	2	
Sandbar shark	0.25	1	2	
Ocean sunfishes	0.25	3		
Porbeagle	0.17	1	1	
Silky shark	0.17	1	1	
Basking shark	0.08			1
Billfishes	0.08	1		
Blue marlin	0.08	1		
Dusky shark	0.08		1	
Greater Shearwater	0.08	1		
Longfin mako	0.08		1	
Pomfrets	0.08	1		
Sharks	0.08	1		
Skates and rays	0.08	1		
Skipkack	0.08		1	
Snake mackerel	0.08	1		
Wahoo	0.08		1	

Yellowfin Tuna.—There were significant differences in catch rates of three species in yellowfin tuna targeted sets due to the baiting method, but the direction and magnitude of the effect did not suggest any consistent pattern (Table 6). The catch rate of the target species, yellowfin tuna, was significantly reduced by approximately 22% when using the non-offset 16/0 circle hook with single hooked sardine bait compared to a non-offset 16/0 circle hook with threaded sardine bait. Escolar was similarly significantly reduced in catch rate (28%), and about half of this catch was retained (117 of 224). CPUE of lancetfish, a major bycatch species, was increased 15% by the treatment. Most (approximately 88%) lancetfish were also discarded dead, but baiting method had no significant effect on capture mortality (Table 6) for this or any other species.

Bigeye Tuna.—In bigeye tuna–targeted sets there were no significant differences in catch rate or boatside mortality when using non-offset 18/0 circle hooks compared to 10° offset 18/0 circle hooks for the top five captured species and other species of interest (Table 7). There was also no consistent trend in the direction of the impact of using non-offset circle hooks (Table 7). We also found no significant decrease in the catch rates of undersized swordfish (<120 cm from the tip of the lower jaw to tail fork) on the BET-0-Sq treatment (t = 0.527, df = 25, P = 0.60).

Non-Fish Bycatch (Sea Turtles, Marine Mammals, and Seabirds).—During all three experiments we observed the capture of 16 leatherback sea turtles, all of which were released alive. One of the leatherbacks was released with gear attached because the leader broke; the remaining 15 were all released without any gear attached and in 13 of the cases they were noted to be in good condition (two cases had no information on the condition at the time of release). For leatherbacks, no clear pattern of capture as a function of the experimental treatments was apparent in the data. Four leatherbacks were captured in the swordfish target study (CPUE approximately 0.10 per 1000 hooks), three on the SWO-0-S treatment, and one on the control SWO-10-T (Table 2). Seven leatherbacks were captured in the yellowfin tuna target study (CPUE approximately 0.12 per 1000 hooks), 1 on a YFT-0-S treatment, 4 on the control YFT-0-T (Table 3), and 2 were on an unknown treatment. In this experiment, all leatherbacks were either foul hooked, entangled, or of unknown hook location. Five leatherbacks were captured in the bigeye tuna target study (CPUE approximately 0.14 per 1000 hooks), 1 on the BET-0-Sq treatment, 2 on the control BET-10-Sq, and 2 were unknown (Table 4). Small sample size (n = 3) precluded significance testing. Most leatherbacks (14 of 16) were foul hooked or entangled.

We captured eight loggerhead sea turtles and all appeared to either dive or swim away vigorously without any gear attached. Two of the loggerheads were captured in the swordfish target study (CPUE approximately 0.05 per 1000 hooks), 1 was on the SWO-0-S treatment, and 1 was on the control SWO-10-T (Table 2). No loggerheads were captured in the yellowfin tuna target study. Six loggerheads were captured in the bigeye tuna target study (CPUE approximately 0.17 per 1000 hooks), 4 on the BET-0-Sq treatment, and 2 on the control BET-10-Sq (Table 4). Most loggerheads (6 of 8) were mouth hooked, and we found the same number of mouth hooked individuals in treatments and controls in the swordfish-targeted and bigeye tuna–targeted sets.

Three pilot whales and two Greater Shearwaters were captured during the experiments. One pilot whale was mouth hooked on the control BET-10-Sq, and two were entangled on lines with treatment BET-0-Sq in bigeye tuna targeted sets (Table 4). The two entangled pilot whales were released alive after all gear was removed. The one mouth hooked pilot whale was released alive with approximately 0.6 m of line remaining. One Greater Shearwater was foul hooked on treatment SWO-10-T on a vessel targeting swordfish (Table 2) and was released alive. The other Greater Shearwater was entangled and found dead on treatment BET-10-Sq on a vessel targeting bigeye tuna (Table 4).

Table 5. Catch per unit effort (CPUE, catch per 1000 hooks) and mortality in swordfish-targeted sets for the top five most caught and other species of interest. ns = not significant, ** $P < 0.01$. SWO-10-T = 10° offset 18/0 circle hook with threaded mackerel bait, SWO-0-S = non-offset 18/0 circle hook with single hooked mackerel bait.

	CPUE			% mortality		
Common name	Control SWO-10-T	Treatment SW0-0-S		Control SWO-10-T	Treatment SW0-0-S	
Swordfish	33.54	32.21	ns	65.4	69.6	ns
Requiem shark	29.49	26.85	ns	48.4	62.2	ns
Night shark	16.47	22.24	ns	84.0	72.9	ns
Atlantic sailfish	10.36	5.64	**	39.5	37.3	ns
Tiger shark	4.48	3.69	ns	0.7	0.9	ns
White marlin	3.24	2.10	ns	20.0	25.6	a
Blue marlin	2.71	3.81	ns	50.0	50.0	b

a Insufficient sample size, only one paired sample.

b Insufficient sample size, no paired samples, pooled mortality was 27.3%.

Discussion

Across all three studies we saw no consistent decreases in CPUE or mortality due to non-offset circle hooks or single hooking baiting techniques. The only significant bycatch reduction for a species of concern was found for Atlantic sailfish on vessels targeting swordfish when using the treatment of non-offset 18/0 single hooked mackerel bait compared to 10° offset 18/0 circle hooks with threaded mackerel bait. A recent review noted that there has been no study showing a significant decrease in catch rates of circle hooks compared to J-hooks for billfishes (Serafy et al. 2009). In a recreational fishery, sailfish showed significantly more injuries and greater severity of injuries when caught on J-hooks compared to those caught on circle hooks but there were no differences due to the degree of offset of circle hooks (<4° compared to about 15°, Prince et al. 2002). The observed 46% decrease in Atlantic sailfish catch in light of these other findings would argue that the observed reduction may be due in large part to the baiting technique and not hook offset. Unfortunately, our design does not allow for such a determination because hook offset and baiting technique were confounded in the treatments. We speculate that for single hooked mackerel bait, the sailfish may be tearing off part of the bait, thus having a lower probability of being hooked on this treatment and having little to do with the effect of circle hook offset. Whatever the mechanism, this result shows promise for bycatch reduction of Atlantic sailfish when using non-offset 18/0 circle hooks with single hooked mackerel bait.

We occasionally found a significant reduction in landed catch due to our tested bycatch reduction technologies. The observed reduction of 22% and 28% for yellowfin tuna and escolar on vessels targeting yellowfin tuna was a significant cost to using single hooked sardine bait compared to the threaded sardine bait, both on 16/0 non-offset circle hooks. We suspect that the reduced catch of the target species yellowfin tuna and escolar on single hooked sardines may be directly related to the tendency of the bait to pull off the hook as sardines are very soft and the skin is also thin and weak.

Table 6. Catch per unit effort (CPUE, catch per 1000 hooks), and mortality in yellowfin tuna–targeted sets for the top five most caught and other species of interest. ns = not significant, * $P < 0.05$. YFT-0-T = non-offset 16/0 circle hook with threaded sardine bait, YFT-0-S = non-offset 16/0 circle hook with single hooked sardine bait.

	CPUE			% mortality		
Common name	Control YFT-0-T	Treatment YFT-0-S		Control YFT-0-T	Treatment YFT-0-S	
Lancetfishes	13.22	15.22	*	87.5	89.3	ns
Yellowfin tuna	9.95	7.81	*	38.1	34.4	ns
Escolar	6.74	4.83	*	27.4	23.0	ns
Swordfish	3.46	4.14	ns	61.2	71.5	ns
White marlin	2.04	2.88	ns	21.4	23.8	ns
Bluefin tuna	2.50	1.32	ns	a	a	

a Insufficient sample size, only one paired sample, pooled mortality 78.8%.

The bycatch of most species (other than Atlantic sailfish), particularly sea turtles, sharks, and undersized swordfish, all showed either no significant reductions or no consistent pattern of directionality in catch rates or mortality rates on any of our potential bycatch reduction treatments. We note that in most cases, lack of statistical significance may be due to the relatively low number of individuals captured, which resulted in few paired samples. Few paired samples could be due to hook and/or bait configurations that resulted in fewer bycatch species becoming hooked, or it could be due to bait loss in some treatments such as single hooked fish (Ward and Myers 2007). The only other bycatch species that showed a significant result, except for Atlantic sailfish, was lancetfish which evidenced a 15% increase in catch on single hooked sardine bait compared to threaded sardine bait.

Mixed results have been found in direct comparisons of circle hooks to J-hooks (e.g., Kerstetter and Graves 2006b, Gilman et al. 2007, Carruthers et al. 2009). Watson et al. (2005) found significant effects (sometimes in opposite directions) of, and significant differences between, non-offset and 10° offset circle hook catch rates compared to J-hooks on swordfish and blue sharks. Watson et al. (2005) also found no significant difference between the reduction in catch rates of non-offset circle hooks and 10° offset circle hooks on sea turtles (loggerheads and leatherbacks), but their design did not allow for paired comparisons of non-offset and 10° offset circle hooks within their sets. Epperly et al. (2012) found that the odds of a swordfish being deep hooked on the 10° offset 18/0 circle hook were significantly greater than the odds associated with the non-offset 18/0 circle hook, and that the odds of boating a dead swordfish were greater for some hooking locations when using the 10° offset hook. Similarly, the authors found that the odds of boating a dead bigeye tuna were greater on the offset hook.

Our estimated turtle catch rates on circle hooks were comparable to those found by Watson et al. (2005), for all their treatments except J-hooks with squid bait, which were about 0.2 turtles (loggerheads and leatherbacks) per 1000 hooks. Alternatively, other studies found somewhat greater circle hook bycatch rates, such as 0.41 loggerheads per 1000 hooks observed in the Mediterranean on 16/0 10° offset circle hooks (Piovano et al. 2009). These comparisons suggest that the magnitude of bycatch reduction for sea turtles in pelagic longline fisheries due to circle hook use is probably region, season, and fishery specific (Gilman et al. 2006).

Table 7. Catch per unit effort (CPUE, catch per 1000 hooks), and mortality in bigeye tuna targeted sets for the top five most caught and other species of interest. ns = not significant. BET-10-Sq = a 10° offset 18/0 circle hook with squid bait, BET-0-Sq = non-offset 18/0 circle hook with squid bait.

	CPUE			% mortality		
Common name	Control BET-10-Sq	Treatment BET-0-Sq		Control BET-10-Sq	Treatment BET-0-Sq	
Swordfish	9.80	11.07	ns	74.1	68.8	ns
Yellowfin tuna	5.79	7.03	ns	38.3	38.4	ns
Dolphinfishes	7.29	5.86	ns	19.4	16.2	ns
Blue shark	5.26	5.56	ns	3.0	19.6	ns
Pelagic stingray	9.56	6.11	ns	0.0	0.0	
Bluefin tuna	1.99	3.53	ns	78.6	78.6	ns
Manta ray	3.02	2.14	ns	0.0	0.0	
Bigeye tuna	7.62	5.66	ns	42.1	51.2	ns
White marlin	1.55	2.03	ns	a	a	

a Insufficient sample size, no paired samples, pooled mortality 26%.

All of the sea turtles were released alive and seemed to be in good condition, except for one leatherback released with the line attached. Sea turtles captured on gear where hooks are more likely to be swallowed may suffer higher mortality (Gilman et al. 2007), but post-hooking mortality due to either the direct injuries from the gear (Valente et al. 2007) or from the stress of capture remains unquantified for sea turtles. We encourage the further application of methods such as satellite tagging, which has been successfully applied to billfishes (e.g., Horodysky and Graves 2005, Graves and Horodysky 2008) to evaluate post-hooking mortality in sea turtles (Swimmer et al. 2006, Sasso and Epperly 2007).

For endangered and threatened species such as sea turtles, our results and those of others (Swimmer et al. 2010) imply that there is a relatively small conservation benefit in catch rates or boatside mortality of non-offset circle hooks compared to minor offset (10° or less) circle hooks. Large sample sizes would be needed to detect differences in catch rate or mortality of protected species due to offset or baiting technique. For example, a power analysis (P = 0.8, α = 0.05) utilizing the variance estimated from the pooled catch rates of leatherback sea turtles in the yellowfin tuna–targeted sets suggests a sample size of at least 4185 sets would have been needed to detect a 25% decrease in CPUE. Although a conservative approach would favor non-offset circle hooks, other bycatch mitigation strategies could be considered, such as avoiding bycatch hotspots through communication programs, time-area closures, and further research on baiting techniques. We recommend basic fishery independent research that would help predict habitat conditions that favor a species of concern and lead to predictive models that could greatly mitigate bycatch. Bycatch mitigation research in other fisheries with larger detrimental population level impacts to sea turtles (Lewison and Crowder 2007) and other species of concern may potentially yield greater conservation benefits than pursuit of minor gains in bycatch reduction due to changes in circle hook offset (10° or less).

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Appendix 1. Species and authorities for catch and bycatch from 2005 experimental sets in the US Atlantic and Gulf of Mexico pelagic longline fishery.

Species and authority	Common name
Acanthocybium solandri (Cuvier in Cuvier and Valenciennes, 1832)	Wahoo
Alepisauridae spp.	Lancetfishes
Alopias spp.	Thresher sharks
Alopias superciliosus (Lowe, 1841)	Bigeye thresher
*Alopias vulpinu*s (Bonnaterre, 1788)	Common thresher
Bramidae spp.	Pomfrets
Carcharhinidae spp.	Requiem sharks
Carcharhinus falciformis (Müller and Henle, 1839)	Silky shark
Carcharhinus leucas (Müller and Henle, 1839)	Bull shark
Carcharhinus longimanus (Poey, 1861)	Oceanic whitetip shark
Carcharhinus obscurus (Lesueur, 1818)	Dusky shark
Carcharhinus plumbeus (Nardo, 1827)	Sandbar shark
Carcharhinus signatus (Poey, 1868)	Night shark
Caretta caretta (Linnaeus, 1758)	Loggerhead sea turtle
Cetorhinus maximus (Gunnerus, 1765)	Basking shark
Chondrichthyes spp.	Sharks
Coryphaena spp.	Dolphinfishes
Dermochelys coriacea (Vandelli, 1761)	Leatherback sea turtle
Euthynnus pelamis (Linnaeus, 1758)	Skipjack
Galeocerdo cuvier (Péron and Lesueur in Lesueur, 1822)	Tiger shark
Gempylus serpens Cuvier, 1829	Snake mackerel
Ginglymostoma cirratum (Bonnaterre, 1788)	Nurse shark
Globicephala spp.	Pilot whales
Istiophoridae spp.	Billfishes
Istiophorus platypterus (Shaw in Shaw and Nodder, 1792)	Atlantic sailfish
Isurus oxyrinchus Rafinesque, 1810	Shortfin mako
Isurus paucus Guitart Manday, 1966	Longfin mako
Lamna nasus (Bonnaterre, 1788)	Porbeagle
Lampris guttatus (Brünnich, 1788)	Opah
Lepidocybium flavobrunneum (Smith, 1843)	Escolar
Makaira nigricans Lacépède, 1802	Blue marlin
Mobulidae spp.	Manta rays
Molidae spp.	Ocean sunfishes
Prionace glauca (Linnaeus, 1758)	Blue shark
Pteroplatytrygon violacea (Bonaparte, 1832)	Pelagic stingray
Puffinus gravis (O'Reilly, 1818)	Greater Shearwater
Ruvettus pretiosus Cocco, 1833	Oilfish
Sphyraenidae spp.	Barracudas
Sphyrna lewini (Griffith and Smith, 1834)	Scalloped hammerhead shark
Sphyrnidae spp.	Hammerheads
Tetrapturus albidus Poey, 1860	White marlin
Tetrapturus georgii Lowe, 1841	Roundscale spearfish
Tetrapturus pfluegeri Robins and de Sylva, 1963	Longbill spearfish
Tetrapturus spp.	Spearfishes
Thunnus alalunga (Bonnaterre, 1788)	Albacore tuna
Thunnus albacares (Bonnaterre, 1788)	Yellowfin tuna
Thunnus atlanticus (Lesson, 1831)	Blackfin tuna
Thunnus obesus (Lowe, 1839)	Bigeye tuna
Thunnus spp.	Tunas
Thunnus thynnus (Linnaeus, 1758)	Bluefin tuna
Xiphias gladius Linnaeus, 1758	Swordfish