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Article

Assessment of "weak hook" effects on fish catches and sizes in a pelagic longline fishery

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ABSTRACT

Objective: We sought to evaluate the effectiveness of "weak hooks" in reducing the bycatch of Bluefin Tuna *Thunnus thynnus* in the U.S. Gulf of America (also known as Gulf of Mexico) pelagic longline fishery while maintaining catch rates and size distributions of the primary target species, Yellowfin Tuna *T. albacares*.

Methods: A total of 416 experimental pelagic longline sets were conducted aboard commercial vessels in the Gulf of America. Two treatments were compared: a 4.00-mm-diameter circle hook (control) and a custom-made 3.65-mm-diameter circle hook (weak), which were deployed in an alternating fashion. Fish catches and sizes were recorded for each hook type, and catch rates and size distributions were compared statistically. A hook straightening metric was paired with fish fork length for 888 control hooks and 863 weak hooks that caught Yellowfin Tuna. Hook time recorders and time depth recorders were used to estimate escape times for animals that bent weak hooks.

Results: No significant differences were observed in catch rates between hook types for any of the captured species except Bluefin Tuna, whose catch rates were 46% lower on weak hooks. No differences in size frequency distributions were observed for Yellowfin Tuna between hook types, but larger Bluefin Tuna were caught less frequently on weak hooks. Hook gap widening increased with fish size and was over twice as pronounced for weak hooks compared to control hooks. Approximately 50% of escaped animals that bent weak hooks escaped within 5 min.

Conclusions: Weak hooks effectively reduced the bycatch of large Bluefin Tuna without significantly affecting the catch rates or size distributions of the primary target species or other encountered species. The increased likelihood of hook straightening on weak hooks suggests a mechanism for selective release of larger Bluefin Tuna, and escape data indicate rapid release for many animals. These results support the use of weak hooks as a tool for reducing bycatch of large Bluefin Tuna and promoting more sustainable fisheries.

KEYWORDS: Bluefin Tuna, bycatch reduction, commercial fisheries, fisheries management, gear selectivity, pelagic longline, terminal tackle, *Thunnus thynnus*, weak hooks

LAY SUMMARY

Commercial fisheries that target Yellowfin Tuna and Swordfish also capture fish species/sizes that are illegal to retain or have no economic value. We found that using a weaker hook than the industry standard reduced the catch of Bluefin Tuna without reducing the target catch.

INTRODUCTION

The Gulf of America (also known as Gulf of Mexico) holds significant relevance within the U.S. commercial pelagic longline (PLL) fishery for Yellowfin Tuna *Thunnus albacares*, accounting for 26–43% of the overall U.S. Atlantic Yellowfin Tuna PLL landings from 2017 to 2021 (National Marine Fisheries Service, 2022). The primary target species of the Gulf of America PLL fishery are Yellowfin Tuna and, to a

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lesser extent, Swordfish *Xiphias gladius* (average yearly landings of 306.0 metric tons of Yellowfin Tuna and 214.7 metric tons of Swordfish from 2017 to 2021; National Marine Fisheries Service, 2022). However, many species are incidentally captured, some of which are both economically valuable and of conservation concern, including the Bluefin Tuna *Thunnus thynnus* (Beerkircher et al., 2002; Orbesen et al., 2017; Swimmer et al., 2017; Teo & Block, 2010).

The Bluefin Tuna is widely distributed across the Atlantic Ocean, Gulf of America, and Mediterranean Sea (Block et al., 2005; Lutcavage et al., 2000; Rooker et al., 2008; Wise & Davis, 1973). The presence of distinct spawning areas in western Atlantic and Mediterranean waters has led the International Commission for the Conservation of Atlantic Tunas to divide Bluefin Tuna into eastern and western management units. In the western Atlantic, two spawning areas have been identified: The primary spawning area is the Gulf of America (Richards, 1976; Rooker et al., 2008; Teo et al., 2007), and a secondary location known as the Slope Sea has recently been confirmed (Hernández et al., 2022; Richardson et al., 2016; Rypina, et al., 2019). Timing of occurrence varies among years based on oceanographic conditions, but a portion of the western stock of Bluefin Tuna concentrates in the Gulf of America from December to March and the majority of fish leave the Gulf of America by the end of June (Block et al., 2005; Galuardi et al., 2010; Teo et al., 2007). These fish are typically in the "giant" size-class (>205.7 cm curved fork length) and are more than five times the average weight of Yellowfin Tuna caught by the Gulf of America fleet (based on an average observed dressed weight of 41 kg for Yellowfin Tuna and 208 kg for Bluefin Tuna in this study). To conserve spawners, fishers are prohibited from targeting Bluefin Tuna in the Gulf of America (National Oceanic and Atmospheric Administration [NOAA], 1981); however, the species is incidentally caught by PLL fleets targeting Yellowfin Tuna and Swordfish, and some incidental retention is permitted. Amendment 7 to the 2006 Consolidated Highly Migratory Species Fishery Management Plan (NOAA, 2014) established an individual Bluefin Tuna quota (IBQ) program that under Amendment 13 (NOAA, 2023), annually allocates IBQ to each active Gulf of America fishing vessel. All dead Bluefin Tuna greater than 185.42 cm curved fork length must be retained, and all dead Bluefin Tuna count towards the vessel IBQ (NOAA, 2014). Vessels are required to have a minimum of 0.25 metric tons of IBQ to fish in the Gulf of America; once a vessel reaches its allocation of IBQ, the owner is required to either lease more quota from another vessel before the beginning of the next quarter or cease all PLL fishing activities for the remainder of the year (NOAA, 2016).

The relatively warm waters of the Gulf of America, coupled with the strenuous demands associated with spawning activities, result in Bluefin Tuna at-vessel mortality rates as high as 68% (Orbesen et al., 2019). This also leads to poor meat quality in many retained fish (Foster et al., 2015), which typically results in lower market prices than fish that are captured in other regions (National Marine Fisheries Service, 2022). These challenges have led to a common desire among both fishery managers and the Gulf of America PLL captains to minimize Bluefin Tuna interactions.

The western stock of Bluefin Tuna has historically been considered both overfished and undergoing overfishing, which led the Standing Committee on Research and Statistics (International Commission for the Conservation of Atlantic Tunas) to implement a 15-year recovery plan in 2007. The most recent stock assessment on the western stock of Bluefin Tuna (Standing Committee on Research and Statistics, 2021) found that the stock is not currently subject to overfishing; however, biomass reference points to determine stock status were not estimated due to uncertainty in recruitment potential. Given the uncertainties surrounding western stock status and recruitment, minimizing the incidental catch and subsequent mortality of adult Bluefin Tuna in the U.S. Gulf of America PLL fishery remains a management priority. Advancements in fishing technology, as investigated here, may allow fishers to continue to capture their main targeted species, Yellowfin Tuna and Swordfish, while minimizing the incidental catch and dead discard of Bluefin Tuna and other incidentally caught species (Campbell & Cornwell, 2008).

In this study,[1] we examined whether reducing the wire diameter of 16/0 circle hooks from 4.00 to 3.65 mm would reduce the observed catch of Bluefin Tuna in the U.S. Gulf of America PLL fishery. We chose to experiment with variations in a 16/0 hook, as this is the most frequently used hook size in the fishery and is the smallest allowed hook in the U.S. Gulf of America for sea turtle conservation purposes. Although Bluefin Tuna catch reduction is a priority, changes in terminal tackle could also alter the catch rate and size composition of both target and bycatch species. Therefore, to better understand the overall impact of using a "weak" 16/0 hook versus the industry standard ("control") 16/0 hook in the fishery, our objectives were to (1) compare catches of Bluefin Tuna, target species, and other bycatch species; (2) compare the size frequencies of captured Yellowfin Tuna and Bluefin Tuna; (3) examine relationships between fish size (length) and hook deformity (gap width [GW]) for captured Yellowfin Tuna; and (4) reveal the apparent times that fish were on the line from hooking to escapement from weak hooks.

METHODS

Experimental design

Eight commercial PLL vessels and their crews were used to compare weak and control hooks in reducing the incidental Bluefin Tuna catch rate associated with PLL gear in the Gulf of America. The control treatment was an industry standard Mustad 16/0 circle hook with no offset (Model 39960D), constructed of 4.0-mm round-stock steel wire. The experimental weak hook treatment was a custom-made Mustad 16/0 circle hook with no offset (Model 39988D), constructed from

1 Reported here are the results of 416 strong–weak hook experimental sets. Results of analyses performed on the first 311 sets (2008–2010) appeared in a report on the final rule to require the use of circle hooks on pelagic longline vessels in the Gulf of America (Menashes, 2011). In this paper, we analyze all data obtained from 2008 to 2012 in a statistically more robust fashion; therefore, our results supersede those presented by Menashes (2011). Our findings remain relevant to U.S. Gulf of America fishery management but also to management of PLL fisheries operating in Atlantic waters, where mandatory weak hook use is currently being implemented as part of the Atlantic Pelagic Longline Take Reduction Plan (NOAA, 2023).

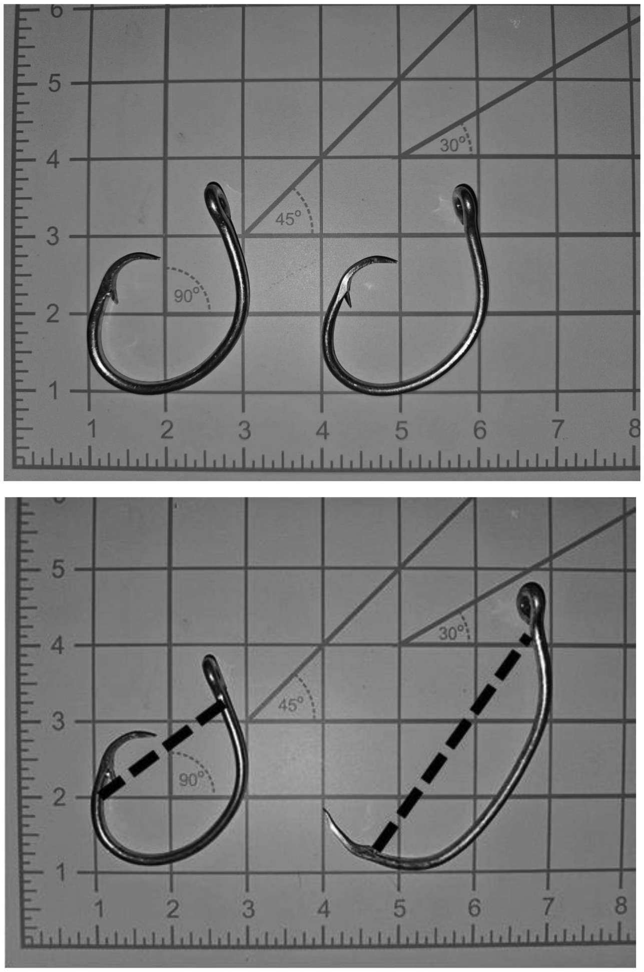

Figure 1. A control 16/0 circle hook (top panel, left) compared to a weak 16/0 circle hook (top panel, right) and an unfished weak 16/0 circle hook (bottom panel, left) compared to a bent weak 16/0 circle hook (bottom panel, right). Black dashed lines indicate how the gap width was measured.

3.65-mm round-stock steel wire (Figure 1). Control and weak hooks were alternated on the longline for a minimum of 400 total hooks per set. Three to five hooks were deployed between each float. Consistent within trips were the following: the number and spacing of hooks between floats, the float line and gangion length, and the monofilament color. Gangions were constructed of 1.8–2.0-mm-diameter monofilament, ranging from 43 to 77 m in length, with a swivel placed 9–26 m above the hook. Float line lengths ranged from 15 to 37 m. As required by federal regulation, gangion lengths were at least 10% greater than float line lengths for sea turtle conservation purposes. Hook depths, calculated as the gangion length plus the float line length, ranged from 62 to 101 m, although actual hook depths varied based on catenary sag and oceanographic conditions. Mainline length per set varied from 28 to 71 km. Spanish Sardine *Sardinella aurita* were the primary bait preference, along with squid *Illex* spp. and Atlantic Thread Herring *Opisthonema oglinum*. Each gear section maintained uniform bait selection. Other than the experimental design requirements, captains were allowed to fish normally and to choose the location of fishing, length of trips, and total number of hooks fished.

Data collection

All participating vessels carried NOAA-trained observers. The observers and the captains were well versed in the experimental design, and each observer was trained in safety at sea; fish, marine mammal, and seabird identification; data collection and recording; and the operation of a PLL fishing vessel. Observers collected fishery data as described by the Southeast Fisheries Science Center's Pelagic Longline Observer Program (Beerkircher et al., 2002), with minor modifications to accommodate the experiment. The time and location of each section of gear were recorded as it was deployed and retrieved, as was sea surface temperature, via each vessel's existing electronic equipment. For each captured animal, the section number, treatment (hook model), time landed on deck, and species identity were recorded. Individuals that came off their hook at boat side were counted as captures. Length measurements to the nearest centimeter were taken for boarded animals, while lengths were estimated for animals that were not boated. A carcass tag was affixed to each retained fish to allow the dressed weight (eviscerated carcass with head and fins removed), as measured during unloading at the dock, to be matched with the specific data collected for that animal at sea.

At retrieval, hooks that were observed to be bent with no observed catch were recorded as species "unknown"; the hooks were collected, and their condition was documented. All hooks that caught Yellowfin Tuna were tagged and retained to examine for hook deformation, if any, resulting from the combined physical forces exerted by the fish, gear, and sea conditions.

To quantify fish escapement time associated with weak hooks, a proportion of the sets incorporated electronic hook time recorders (HTRs; HT 600 Hook Timer; Lingren Pitman, Pompano Beach, Florida) and time depth recorders (TDRs; LAT1100; Lotek Wireless, Inc., Newmarket, Ontario), which were deployed only on gangions that were attached to weak hooks ($n = 150$ per set). The HTRs function as stopwatches that are triggered when an animal pulls on the leader, thereby recording the elapsed time (hours and minutes) from the start of the fish–hook interaction until the hook is retrieved. The time of interaction was estimated by subtracting the elapsed time from the HTR from the boarding time. The TDRs record depth and ambient water temperature over time at a 1–2-min resolution (depending on the duration of the trip), which indicates the vertical movement of the gangion throughout the deployment. When the TDR is deployed, it sinks to a relatively uniform depth until a fish–hook interaction occurs, which is denoted by a distinct increase in TDR movement activity. If escapement occurs, TDR activity rapidly declines and returns to a uniform depth. By examining the HTR and TDR data jointly, we were able to determine the elapsed time between the first fish–hook interaction and escapement for animals associated with straightened weak hooks. The HTRs were placed between the mainline and gangion, while the TDRs were attached at the swivel about 9 m above the hook. With their small dimensions, distance from the hook, and minimal in-water weight (~1.7 g), it was assumed that the TDRs had no effect on the fishing performance of the gear.

Table 1. Total catch of fish, sharks, sea turtles, and marine mammals caught during an alternating-hook experiment using industry standard (control) 16/0 hooks and weak 16/0 hooks in the Gulf of America pelagic longline fishery, as recorded by Pelagic Longline Observer Program observers (2008–2012). Asterisks indicate taxa that were analyzed. For meaningful interpretations of results, we analyzed data for taxa with at least 20 individuals caught.

Taxon	Control	Weak	Unknown	Total
Yellowfin Tuna *Thunnus albacares* (total)*	1,682	1,630	19	3,331
Yellowfin Tuna (retained for sale)*	1,313	1,234	14	2,561
Lancetfish (Alepisauridae)*	958	884	8	1,850
Dolphinfish *Coryphaena* spp.*	483	435	7	925
Skipjack Tuna *Katsuwonus pelamis**	322	329	5	656
Escolar *Lepidocybium flavobrunneum**	317	327	2	646
Blackfin Tuna *Thunnus atlanticus**	224	256	8	488
Wahoo *Acanthocybium solandri**	211	164	0	375
Swordfish *Xiphias gladius* (total)*	140	150	3	293
Swordfish (retained for sale)*	40	29	1	70
Pelagic Stingray *Pteroplatytrygon violacea**	97	87	0	184
White Marlin *Kajikia albida*/Roundscale Spearfish *Tetrapturus georgii* (combined)*	70	102	4	176
Blue Marlin *Makaira nigricans**	79	78	1	158
Bluefin Tuna *Thunnus thynnus**	87	47	1	135
White Marlin*	37	48	0	85
Pomfret (Bramidae)*	42	37	0	79
Barracuda (Sphyraenidae)*	32	43	2	77
Atlantic Bonito *Sarda sarda**	36	30	0	66
Frigate Mackerel *Auxis thazard**	30	32	0	62
Sailfish *Istiophorus platypterus**	35	27	0	62
Unidentified requiem shark (Carcharhinidae)	23	20	2	45
Unidentified animal (unknown)	18	22	0	40
Unidentified shark (Chondrichthyes)	19	18	0	37
Silky Shark *Carcharhinus falciformis**	20	15	2	37
Sandbar Shark *Carcharhinus plumbeus**	16	15	0	31
Tiger Shark *Galeocerdo cuvier**	17	14	0	31
Unidentified billfish (Istiophoridae)	12	12	0	24
Shortfin Mako *Isurus oxyrinchus*	6	11	2	19
Unidentified mobulid ray (Mobulidae)	8	5	1	14
Oilfish *Ruvettus pretiosus*	6	7	0	13
Longfin Mako *Isurus paucus*	6	4	1	11
Bigeye Tuna *Thunnus obesus*	6	4	0	10
Leatherback turtle *Dermochelys coriacea*	3	5	2	10
Dusky Shark *Carcharhinus obscurus*	6	4	0	10
Bigeye Thresher *Alopias superciliosus*	5	4	0	9
Unidentified tuna *Thunnus* spp.	7	1	0	8
Opah *Lampris guttatus*	4	3	0	7
Albacore *Thunnus alalunga*	1	4	0	5
Sharptail Mola *Masturus lanceolatus*	2	3	0	5
Unidentified mako shark *Isurus* spp.	1	3	0	4
Oceanic Whitetip Shark *Carcharhinus longimanus*	2	0	1	3
Pantropical spotted dolphin *Stenella attenuata*	1	1	1	3
Thresher shark *Alopias* spp.	3	0	0	3
Unidentified sunfish (Molidae)	1	1	0	2
Blue Shark *Prionace glauca*	0	1	1	2
Unidentified spearfish *Tetrapturus* spp.	1	1	0	2
Ocean Sunfish *Mola mola*	2	0	0	2
Longbill Spearfish *Tetrapturus pfluegeri*	1	1	0	2
Snake Mackerel *Gempylus serpens*	0	2	0	2
Unidentified puffer (Tetraodontidae)	2	0	0	2
Scalloped Hammerhead *Sphyrna lewini*	0	1	0	1
Common bottlenose dolphin *Tursiops truncatus*	0	1	0	1
Unidentified ribbonfish (Trachipteridae)	0	1	0	1
Common Thresher Shark *Alopias vulpinus*	1	0	0	1

Species assessed

Only species with at least 20 total individuals captured were examined statistically for differences in CPUE between the two hook types, resulting in an examination of 18 distinct species (Table 1). For the two main target species, Yellowfin Tuna and Swordfish, we also separately analyzed catches and lengths of the fish that were retained. In addition, we examined the White Marlin–Roundscale Spearfish species complex. Fish that were verified to be White Marlin based on morphometrics were coded as WHM, while any fish that could not be verified as a White Marlin was coded as WHX (usually live releases). Given the difficulty of species distinction between White Marlin and Roundscale Spearfish (Shivji et al., 2006) coupled with the uncertainty of species identification for WHX, we considered a species grouping of fish coded as WHX or WHM.

Data analysis

We used SAS version 9.4 (SAS Institute, Cary, North Carolina) to perform all statistical analyses. Species-specific catches associated with the two hook types were compared using the Mantel–Haenszel chi-square test (Mantel & Haenszel, 1959), which follows the approach used in other alternating-hook experiments (Bayse & Kerstetter, 2010; Pacheco et al., 2011; Sales et al., 2010). To control for type I error associated with performing multiple tests (i.e., across species/complexes), we applied the Benjamini–Hochberg (false discovery rate, $\alpha = 0.05$) procedure (Benjamini & Hochberg, 1995). Unadjusted odds ratios and corresponding exact CIs were calculated to assess the relative probability of catch between the two hook types. The estimates of catch differences and related confidence limits were derived by subtracting the odds ratio (and 95% confidence limits) from 1.0 and multiplying the result by 100. Length frequency differences of fish caught on each hook type were examined by using a one-tailed Wilcoxon rank-sum test, with the expectation that weak hooks would capture smaller individuals compared to the control hooks. An analysis was also conducted on a hook straightening metric (i.e., GW) for all hooks that caught Yellowfin Tuna. The measurement taken was the linear distance between the base of the hook eye to the base of the barb (Figure 1, lower panel). Although the two hooks had very similar overall dimensions, the reduction in diameter of the weak hook resulted in a slight difference in the eye-to-notch measurement for unused control hooks (42 mm) versus unused weak hooks (44 mm). A multiple linear regression model was fitted to model the relationship between GW and the independent variables (hook type and Yellowfin Tuna length) and their interaction.

RESULTS

Bluefin Tuna and target species

Eight PLL vessels completed 44 trips in the northern Gulf of America from May 9, 2008, to June 21, 2012. In total, 416 sets were completed following the protocol described above and were used in the analyses. Overall, 244,876 hooks (122,438 of each hook type) were deployed. Vessels fished an average of 588 hooks/set (95% CI = 570–606 hooks/set). A total of 9,960 animals were caught, representing 52 taxa (Table 1). Observers recorded 585 hooks that had straightened to the point of allowing the animal to escape, with a greater number occurring on weak hooks (486), which was statistically different from the number of straightened control hooks (99; Mantel–Haenszel chi-square test: $P < 0.0001$).

In total, 134 Bluefin Tuna were caught during the experiment, of which 47 were caught on weak hooks (35%). A statistically significant reduction in Bluefin Tuna catch was associated with the weak hooks, as there was a 46% decrease in Bluefin Tuna bycatch relative to the control hooks (odds ratio = 0.546, $P = 0.016$; Table 2). A comparison of the length frequency distributions of Bluefin Tuna caught on the two hook types indicated a significant difference in the length compositions of Bluefin Tuna caught on the two hook types (Wilcoxon rank-sum one-tailed test: $P = 0.0422$; Table 3), with large Bluefin Tuna being less frequently caught on the weak hook (Figures 2A, 3A).

Yellowfin Tuna, the primary target species in the Gulf of America PLL fishery, comprised 34% of the total catch by number. The vessels caught a total of 3,312 Yellowfin Tuna, of which 2,547 were retained for eventual sale. Catches of Yellowfin Tuna were equivalent between the two hook types (odds ratio = 0.969, $P = 0.696$) and likewise for the retained component of Yellowfin Tuna catch (odds ratio = 0.939, $P = 0.443$; Table 2). A Wilcoxon rank-sum one-tailed test comparing the size frequency distributions of Yellowfin Tuna indicated no significant difference in the relative size composition of fish caught with the two hook types (Figures 2B, 3B; Table 3).

Four other taxa that are commonly retained for eventual sale in the Gulf of America PLL fishery are Swordfish, Wahoo, dolphinfish, and Escolar. In the case of Swordfish, we examined both the overall catch ratio as well as the catch ratio for retained fish. No significant difference in the catch between the two hook types emerged for any of these taxa (Table 2).

Other bycatch

Of the 9,960 animals that were caught during the experiment, 5,316 were discarded. The predominant bycatch taxon was lancetfish, which made up approximately 35% of the discards. A total of 424 istiophorid billfish were caught during the experiment. No significant difference in catch between the two hook types was detected for any of the billfish species or billfish species groups (Table 2). Overall, 233 sharks were caught during the experiment. No significant differences in the catch between hook types were detected for any of the shark species. Over the course of the experiment, 10 leatherback turtles, three pantropical spotted dolphins, and one common bottlenose dolphin were captured and released alive. Very low catches of sea turtles and marine mammals precluded statistical analyses. Although no reduction of leatherback turtles was observed with the weak hook, observers noted that weak hooks that caught leatherback turtles had partially straightened, making them easier to remove from the animal prior to release.

Yellowfin Tuna hook evaluation

A sample of 889 control hooks and 863 weak hooks that successfully caught Yellowfin Tuna were measured for the hook deformation (GW) analysis. In the regression results, the fish length × hook type interaction emerged as significant, whereby the linear relationships between GW and fish fork length (FL) were $GW = 36.8664 + (0.0536)FL$ for control hooks and

Table 2. Odds ratios and corresponding exact 95% CIs for species counts for control and weak hooks from 414 experimental pelagic longline sets conducted in the Gulf of America between 2008 and 2012. The estimate of reduction rate and related confidence limits were derived by subtracting the odds ratio (and 95% CIs) from 1.0 and multiplying the result by 100. Lowercase “z” indicates a statistically significant difference at $P < 0.05$ for the Benjamini–Hochberg adjusted P-value.

Rank	Taxon	Odds ratio	Mantel–Haenszel chi-square *P*-value	Critical value	Benjamini–Hochberg adjusted *P*-value
1	Bluefin Tuna	0.5463 (0.3828–0.7797)	0.0007	0.0022	0.0161 z
2	Swordfish (retained)	0.7249 (0.4494–1.1693)	0.1854	0.0174	0.5213
3	Silky Shark	0.7500 (0.3840–1.4649)	0.3980	0.0283	0.7042
4	Sailfish	0.7714 (0.4669–1.2744)	0.3096	0.0239	0.6473
5	Wahoo	0.7770 (0.6336–0.9530)	0.0151	0.0065	0.1158
6	Tiger Shark	0.8235 (0.4059–1.6706)	0.5900	0.0391	0.7539
7	Atlantic Bonito	0.8333 (0.5133–1.3528)	0.4601	0.0304	0.7066
8	Pomfret	0.8809 (0.5662–1.3705)	0.5737	0.0370	0.7539
9	Pelagic Stingray	0.8968 (0.6714–1.1980)	0.4608	0.0326	0.7066
10	Dolphinfish	0.9003 (0.7907–1.0250)	0.1125	0.0109	0.4431
11	Lancetfish	0.9222 (0.8413–1.0110)	0.0835	0.0087	0.4431
12	Sandbar Shark	0.9375 (0.4635–1.8963)	0.8574	0.0478	0.8964
13	Yellowfin Tuna (retained)	0.9392 (0.8686–1.0155)	0.1156	0.0130	0.4431
14	Yellowfin Tuna (total)	0.9687 (0.9045–1.0374)	0.3630	0.0261	0.6958
15	Blue Marlin	0.9873 (0.7220–1.3501)	0.9364	0.0500	0.9364
16	Skipjack Tuna	1.0218 (0.8761–1.1917)	0.7835	0.0435	0.8756
17	Escolar	1.0316 (0.8838–1.2042)	0.6932	0.0413	0.8381
18	Frigate Mackerel	1.0667 (0.6482–1.7554)	0.7995	0.0457	0.8756
19	Swordfish (total)	1.0715 (0.8510–1.3492)	0.5568	0.0348	0.7539
20	Blackfin Tuna	1.1432 (0.9553–1.3679)	0.1437	0.0152	0.4722
21	White Marlin	1.2974 (0.8449–1.9922)	0.2237	0.0217	0.5352
22	Barracuda	1.3400 (0.8504–2.1238)	0.2040	0.0196	0.5213
23	White Marlin/ Roundscale Spearfish	1.4575 (1.0751–1.9759)	0.0147	0.0043	0.1158

Table 3. Summary of length (cm) statistics by hook type for Yellowfin Tuna and Bluefin Tuna captured during an alternating-hook study using an industry standard (control) 16/0 circle hook and a weak 16/0 circle hook in the U.S. Gulf of America pelagic longline fishery.

	Control circle hook				Weak circle hook			
Species	**Mean length ± SD**	**Median**	**75th percentile**	***n***	**Mean length ± SD**	**Median**	**75th percentile**	***n***
Yellowfin Tuna	135.7 ± 20.74	141	150	1,599	135.4 ± 20.49	140	149	1,536
Bluefin Tuna	236.9 ± 24.20	240	245	87	232.9 ± 18.71	240	240	47

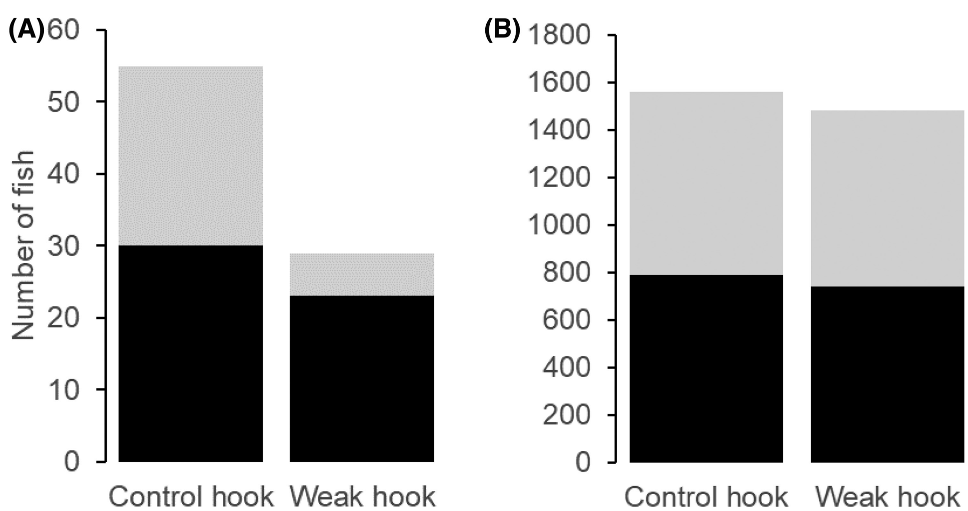

Figure 2. Number of fish captured on control hooks or weak hooks that were below (black) or above (gray) the median length for (A) Bluefin Tuna and (B) Yellowfin Tuna. See Table 3 for median lengths of each species on each hook type.

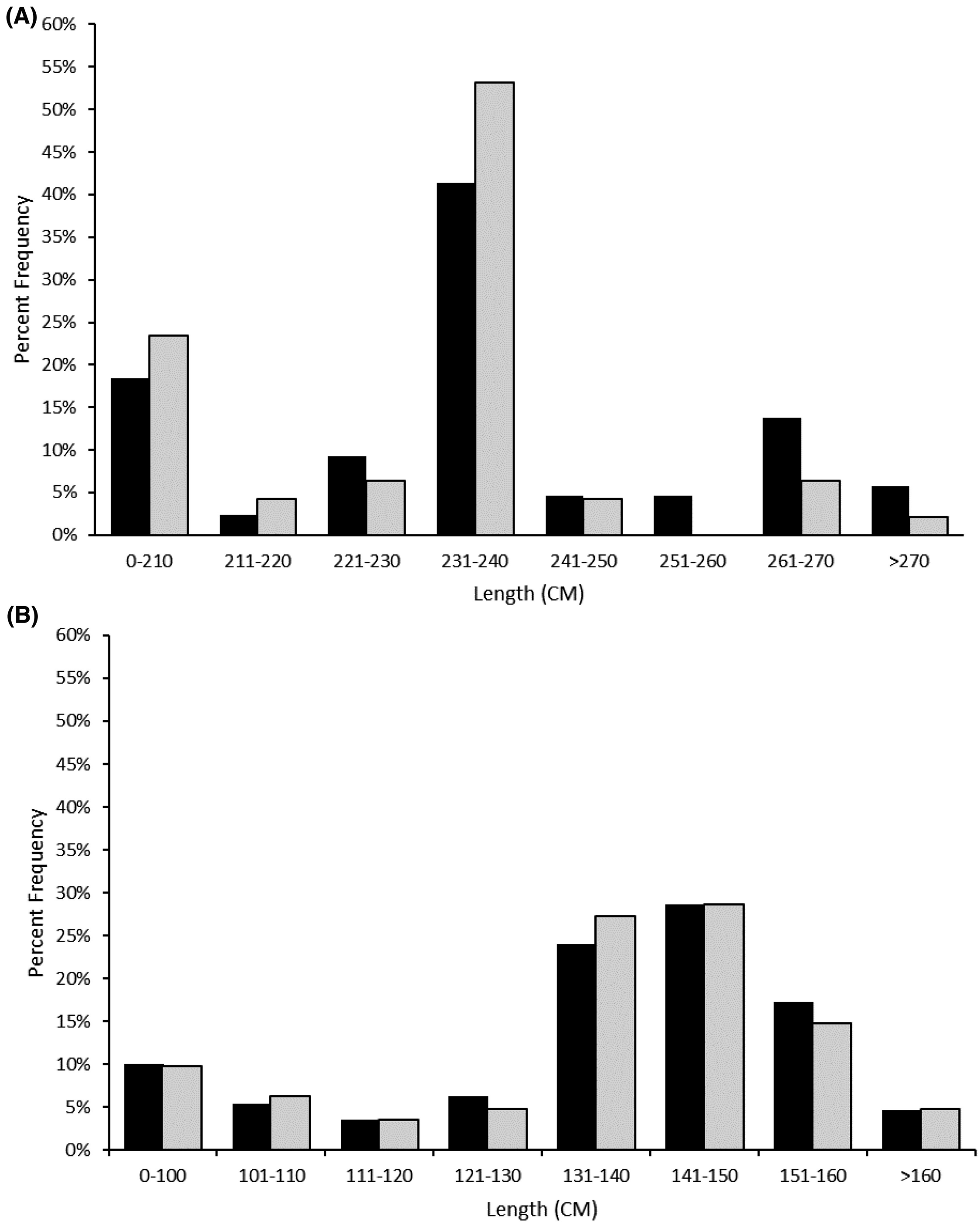

Figure 3. Comparison of length frequencies for fish captured on control (black bars) and weak (gray bars) 16/0 circle hooks in the Gulf of America pelagic longline fishery for (A) Bluefin Tuna and (B) Yellowfin Tuna.

$GW = 29.6974 + (0.1340)FL$ for weak hooks. The difference in slopes indicated that on average, weak hook widening per fish length increment was over twice that of control hooks (Figure 4).

Straightened hook analysis

Of the 486 straightened weak hooks resulting in fish escapement, HTR and TDR data were obtained for 81 hooks. In general, large pelagic fishes exhibit a great deal of vertical movement in the water column after becoming hooked and can spend a substantial amount of time at or near the surface (for example, see Figure 5A). When mortalities occur prior to landing, a gradual to rapid cessation of vertical movements is recorded by the TDR as the gear settles. For large animals, the dead weight of the animal on the line causes the gear to sink deeper than the prior fishing depth. In the case of very large animals (i.e., Bluefin Tuna or mobulid rays), the gear may sink to depths greater than 1,000 m. In contrast, escape events generally result in an immediate cessation of vertical movement measured by the TDR and a quick settling of the gear at or

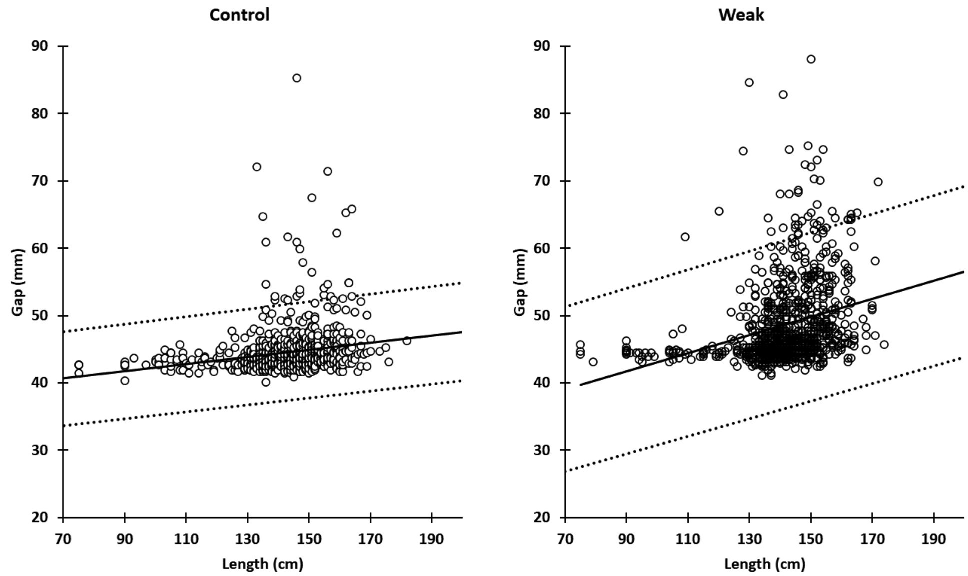

Figure 4. Results of a multiple linear regression model fit (solid line) to model the relationship between hook spread (gap; hook eye to barb notch) and the independent variables of hook type and Yellowfin Tuna length. Fish length is plotted against hook spread for the control hooks and weak hooks. Dotted lines represent upper and lower 95% prediction intervals.

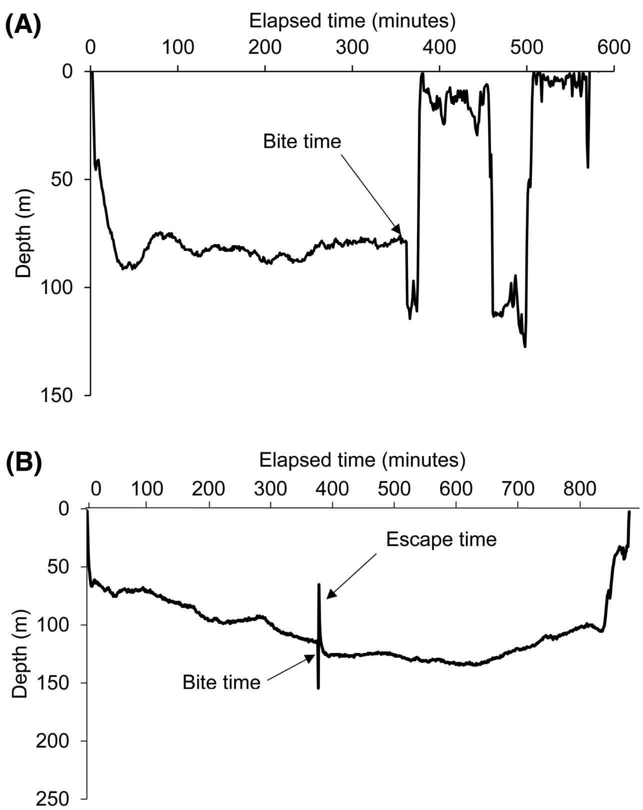

Figure 5. Examples of time and depth profiles (from the time depth recorder) for (A) a hook with a Yellowfin Tuna interaction and (B) a straightened hook that resulted in an escape.

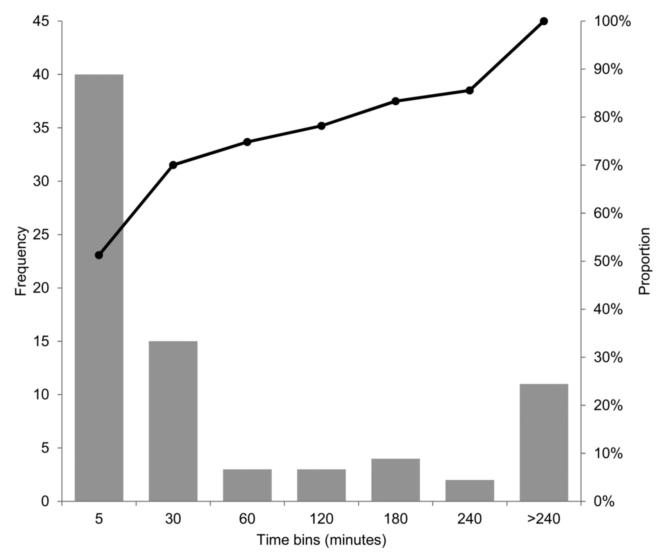

Figure 6. Frequency distribution (primary *y*-axis) and cumulative proportion of records (secondary *y*-axis) for the escapement time of 78 animals that interacted with a gangion consisting of a 16/0 weak hook, a hook time recorder, and a time depth recorder. Hooks were bent to the point of release.

near the depth that the gear was fishing prior to the interaction (Figure 5B).

There were 78 gangions with sufficient HTR and TDR data to allow for escapement time estimates for straightened weak hooks. Of the 78 profiles, 40 (51.3%, CI = 40.2–62.4%) had escape times less than 5 min and over 55 (70%, CI = 60.2–80.8%) of the animals escaped in 30 min or less (Figure 6). Seven animals (9%) apparently straightened the hook near the vessel during haulback. Only one of the TDR profiles provided evidence of a mortality occurring prior to the animal coming off the hook. During this interaction, the gear sank to a depth greater than 1,000 m approximately 10 h prior to being hauled. It remained at that depth until haulback, when only a straightened hook was retrieved. No other large animals or straightened hooks that occurred in the vicinity of this hook were apparent; therefore, we concluded that the straightened hook was likely the result of pulling a large animal off the hook during haulback.

DISCUSSION

Fishery managers face the challenge of mitigating bycatch while minimizing impacts on fishers. Although techniques such as time–area closures can be an effective tool to reduce bycatch, especially when seasonal spawning aggregations occur, they can also pose economic challenges for fishers (Armsworth et al., 2010; J. A. Smith et al., 2020; M. D. Smith & Wilen, 2003) and/or lead to adaptive changes in fisher behavior, which may shift pressure to other species of conservation concern (Abbott & Haynie, 2012). Minor operational changes that decrease bycatch without significantly reducing targeted species catches are preferable and more readily implemented by the fleet (Bigelow et al., 2012; Scott et al., 2022).

While many studies have examined the potential for PLL bycatch reduction via modification of hook shape or hook size (Burns & Kerstetter, 2022; Coelho et al., 2012; Curran & Bigelow, 2011; Gilman et al., 2018; Kerstetter & Graves, 2006; Lima et al., 2023; Serafy et al., 2012), published papers comparing catch (and bycatch) characteristics between "strong" (industry standard) hooks and "weak" hooks are few. Most relevant to the present study are two alternating-hook longline experiments performed by Bayse and Kerstetter (2010) and Bigelow et al. (2012), which both sought to examine the potential for weak hooks to reduce marine mammal bycatch while maintaining target catches. Neither study encountered sufficient quantities of marine mammals to draw inferences about weak hook effects on them, but the quantities of several fish taxa were sufficient for statistical comparisons to be performed.

When comparing our results to those obtained by Bayse and Kerstetter (2010) and Bigelow et al. (2012), it is important to note that (1) in addition to hook size and wire diameter differences among studies, type I error was only controlled for in the present study; (2) unlike our study and that of Bigelow et al. (2012), Bayse and Kerstetter (2010) did not report wire diameter specifications for the four hook types that they tested, and instead, their weak and strong hooks were defined according to the kilograms of force needed to straighten them (pull strength [PS]); and (3) the number and thus spacing of hooks deployed among studies differed widely (i.e., Bayse & Kerstetter, 2010: 4,652–15,568 hooks; Bigelow et al., 2012: 302,738 hooks; present study: 244,876 hooks). Below, we compare our results with those of Bayse and Kerstetter (2010) and Bigelow et al. (2012) in terms of the differences found between the hook types in target species catches, bycatch, target species size, and hook straightening.

Target species catches

In the present study, no catch differences between hooks were found in terms of target species catches (i.e., Yellowfin Tuna and Swordfish), including in their retained catches; however, our study took place in a fishery specifically targeting Yellowfin Tuna, and only a small number of the Swordfish captured were retained (70 of 293). Off Cape Hatteras in the western North Atlantic Ocean, Bayse and Kerstetter (2010) conducted one experiment using 16/0 strong (PS = 113 kg) and weak (PS = 68 kg) hooks with Yellowfin Tuna as the primary target and a second experiment using 18/0 strong (PS = 159 kg) and weak (PS = 102 kg) hooks with Swordfish as the primary target. They found no significant difference in CPUE between control and weak hooks in their 16/0 hook experiments targeting Yellowfin Tuna and Bigeye Tuna *Thunnus obesus*. However, in their experiment targeting Swordfish with 18/0 circle hooks, significantly fewer catches of Swordfish were obtained on their weak hooks. It is important to note that they did not observe any straightened 18/0 hooks. Thus, it is difficult to attribute Swordfish catch rate differences to greater escapement on weak hooks than on strong hooks. Whether the thinner wire diameter of weak hooks makes them more prone than strong hooks to tear through flesh rather than bend warrants further investigation. Bigelow et al. (2012) compared catch rates between weak (4.0-mm-diameter wire) and control (4.5-mm-diameter wire) hooks on deep-set PLL vessels targeting Bigeye Tuna in Pacific waters off Hawaii. Consistent with our study and the Bayse and Kerstetter (2010) study, Bigelow et al. (2012) found no significant catch differences for targeted Bigeye Tuna or Swordfish; however, they did obtain an unexpected result with respect to Yellowfin Tuna catch—namely, significantly higher catches on weak versus strong hooks. The pattern across strong–weak hook studies, therefore, is that weak hook usage can result in little or no reductions in Yellowfin Tuna and Bigeye Tuna catch when these species are the primary targets; further study is required to determine whether weak hook usage results in reduced Swordfish catches.

Bycatch species catches

Working on PLL vessels targeting Yellowfin Tuna in the Gulf of America, we found that reducing the hook diameter from 4.00 to 3.65 mm resulted in a 46% reduction of Bluefin Tuna bycatch, with no apparent effects on the bycatch of other taxa. In their 16/0 hook experiment, Bayse and Kerstetter (2010) reported catch rates for 10 fish taxa, 8 of which they categorized as bycatch. Among the bycatch taxa, the only statistical difference between strong and weak hooks was in Pelagic Stingray bycatch, whereby about twice the number of stingrays were caught on strong versus weak hooks. In their 18/0 hook experiment, Bayse and Kerstetter (2010) reported on catches of four species. For the two they categorized as bycatch (i.e., Night Shark *Carcharhinus signatus* and Silky Shark), catch rates were equivalent between hook types. Bigelow et al. (2012) reported on strong versus weak hook catches for 22 fish species; among the bycatch species, the only statistically significant difference was higher spearfish bycatch on strong hooks. Collectively, all studies (including our own) indicate potential bycatch reduction via weak hook use, although the number of taxa for which there is statistically significant evidence of reduction is limited thus far.

Size differences

In the present study, Bluefin Tuna size differed between the two tested hooks, with more large fish captured on the control hook; however, there were no significant mean size differences for either Yellowfin Tuna or Swordfish. In contrast, Bayse and Kerstetter (2010) reported a significant difference in mean length for Yellowfin Tuna captured on strong and weak 16/0 hooks (114.2 and 109.2 cm, respectively), although their mean dressed weights were not significantly different. In the same 16/0 hook experiment (Bayse and Kerstetter, 2010), no significant differences in Bigeye Tuna mean length or weight were found between strong and weak hooks. Similarly, Bigelow et al. (2012) found no statistically significant differences in length or weight of the targeted catch (Bigeye Tuna) or any of the other 15 species tested. Across experiments, therefore, weak hooks appear to have little or no effect on the mean size of Bigeye Tuna and Swordfish, but one study reported a significant, albeit small, reduction in the mean length of Yellowfin Tuna.

Hook straightening

In our study, we found that our 16/0 weak hooks were nearly five times as likely to be straightened to the point of release when compared to control hooks (486:99). Bayse and Kerstetter (2010) also observed 16/0 weak hooks that were straightened ($n = 7$), including one that was the result of a pilot whale *Globicephala* sp. that escaped during gear retrieval; however, in their experiment with 18/0 hooks, none was straightened. Although the occurrence of straightened hooks was much lower than observed in our study, Bigelow et al. (2012) also found that weak hooks were much more likely to be straightened than control hooks (70:6). However, when examining for hook deformity in hooks that captured Bigeye Tuna, the mean GW was higher for control versus weak hooks (4.14 vs. 3.76 mm) and there was a negative relationship between GW and Bigeye Tuna length. This is in stark contrast to our observations that weak hook widening increased with each fish length increment and was over twice that of control hooks for captured Yellowfin Tuna.

Fish behavior/escapement

When examining HTR and TDR data for straightened hooks, we found that over half of the hooked individuals escaped in less than 5 min. Neither Bayse and Kerstetter (2010) nor Bigelow et al. (2012) used HTR or TDR data to examine escapement times; however, Block et al. (2005) found that Bluefin Tuna were particularly susceptible to high mortality on PLL gear, with mortalities observed in sets with soak times as short as 2 h. Rapid escapement from fishing gear presumably reduces physiological stress and mortality associated with soak times that are often greater than 7 h (Danylchuk et al., 2014; Mohan et al., 2020), although the extent of injuries sustained during the hook straightening process is unknown. McLellan et al. (2015) examined the impact of hook straightening on the soft tissues and bone structures of odontocetes and found that the 16/0 weak hook resulted in a cleaner tear than the other tested hook models, and the gap of the 16/0 hooks was too small to fit over the mandible; however, it is important to note that 18/0 circle hooks were able to pass over the mandible, resulting in a high incidence of bone fractures, and these hooks likely lead to higher catch rates.

Study limitations and implications

The fishers participating in our study were primarily targeting Yellowfin Tuna; however, a proportion of the U.S. PLL fleet specifically targets Swordfish or a mix of the two species. Although there are some similarities between the two fisheries, there are some important differences, including the time of day in which the gear is fished, the use of lightsticks, and the type of bait used, which result in differences in species-specific catch rates and species compositions between the two types of targeting (Orbesen et al., 2017). Bayse and Kerstetter (2010) did conduct experiments in the Swordfish fishery, but the sample size was very small (seven sets) and, when coupled with the lack of observed straightened hooks, more strong–weak hook experiments with the Swordfish fishery are warranted.

All studies observed some level of hook straightening associated with 16/0 weak hooks, which suggests that some relatively rare event bycatch species are capable of straightening these hooks. Rare event species, such as marine mammals, are a high priority for bycatch reduction; however, the rarity of such interactions prohibits obtaining an experimental sample size that is sufficient to test for a significant effect of hook type on catch rates (Bigelow et al., 2012). Although we observed a significant decrease in the catch of Bluefin Tuna associated with weak hooks, their catches were not eliminated. There are likely multiple factors that contribute to the propensity of fish to straighten hooks, including the swimming direction of the fish, the speed of gear retrieval, and the tension on the mainline. A large fish swimming parallel to the mainline can result in the snap sliding along the mainline, thus reducing resistance when compared to a fish swimming perpendicular to the mainline. Opposing water currents may also alter the tension of the mainline, thereby increasing or decreasing resistance.

Hook deformity could affect the structural integrity of the hook or alter its catching ability, necessitating its replacement. Given the greater propensity for hook deformity associated with the weak hooks, crew members will need to be more diligent in the inspection of hooks at retrieval, as a failure to do so could result in subsequent losses of fish and revenue. Replacement of weak hooks may have economic implications for the fleet, but there are potential offsetting gains in avoiding Bluefin Tuna interactions. These include reducing gear loss and damage, time savings associated with handling large tuna, and mitigating costs associated with IBQ management. Reducing the overall number of Bluefin Tuna interactions could help to alleviate the time and cost burden associated with meeting IBQ, as exceeding allocations could ultimately lead to dire consequences for the fisher.

In 2011, a regulation was implemented requiring the year-round use of weak hooks in the U.S. Gulf of America PLL fishery based on evidence that their use significantly reduced the incidental catch of Bluefin Tuna (NOAA, 2011). This rule was modified in 2020 to require weak hooks only during the peak spawning period of Bluefin Tuna (January–June), but some vessels continue to voluntarily use weak hooks throughout the year (NOAA, 2020). Since the implementation of the weak hook regulation, Bluefin Tuna reported landings and dead discards in the Gulf of America have both declined (Figure 7); however, this reduction may also reflect changes in effort as well as the influence of other management measures, including the IBQ system. The National Oceanic and Atmospheric Administration has not defined the area encompassing the Slope Sea for management purposes; however, using the

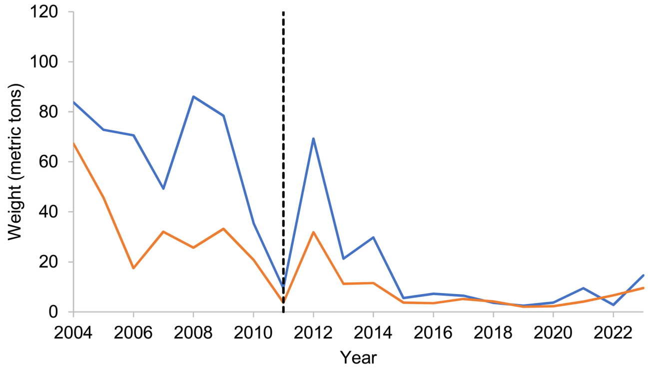

Figure 7. National Marine Fisheries Service-reported landings (orange line) and dead discards (blue line) for Bluefin Tuna in the Gulf of America. The vertical dashed line represents the year of implementation for the weak hook mandate.

boundary defined by Rypina et al. (2019), a small portion falls within the Northeast Distant Gear Restricted Area. This area has a requirement for the use of 18/0 or larger hooks, which was enacted for the conservation of loggerhead turtles *Caretta caretta*. Loggerhead turtles were found to be 3.6 times more likely to swallow a 16/0 circle hook versus an 18/0 circle hook (Stokes et al., 2011). There are no current mandates for weak hook use in any portion of the Slope Sea area, and as Bayse and Kerstetter (2010) highlighted, 18/0 circle hooks have a PS greater than those of both the weak and control hooks used in the present study. As the importance of the Slope Sea for Bluefin Tuna spawning is investigated, thought should be given as to whether weak hook use would be beneficial in this newly verified spawning area.

DATA AVAILABILITY

The data underlying this article cannot be shared publicly, as observer-collected data are considered confidential under the Magnuson–Stevens Fishery Reauthorization Act. For more on data accessibility, please contact the Southeast Fisheries Science Center, Fisheries Statistics Division.

ETHICS STATEMENT

This study meets the ethical guidelines outlined by the American Fisheries Society.

FUNDING

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CONFLICTS OF INTEREST

None declared.

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We dedicate this article to the memory of our esteemed colleague and co-author, Charles Bergmann, whose passion for fisheries research was an inspiration to us all. His presence will be deeply missed. We thank all the dedicated fisherman and observers who helped to make this project possible. We are grateful to Arvind K. Shah for preliminary statistical support, John Mitchell for the development of the weak hook, and Guillermo Diaz for providing summaries of the logbook data. The views and opinions expressed or implied in this article are those of the authors and do not necessarily reflect the position of the NOAA National Marine Fisheries Service. The mention of specific products does not constitute endorsement by the U.S. Government.

REFERENCES

Abbott, J. K., & Haynie, A. C. (2012). What are we protecting? Fisher behavior and the unintended consequences of spatial closures as a fishery management tool. *Ecological Applications*, *22*, 762–777. https://doi.org/10.1890/11-1319.1

Armsworth, P. R., Block, B. A., Eagle, J., & Roughgarden, J. E. (2010). The economic efficiency of a time–area closure to protect spawning Bluefin Tuna. *Journal of Applied Ecology*, *47*, 36–46. https://doi.org/10.1111/j.1365-2664.2009.01738.x

Bayse, S., & Kerstetter, D. (2010). Assessing bycatch reduction potential of variable strength hooks for pilot whales in a western North Atlantic pelagic longline fishery. *Journal of North Carolina Academy of Science*, *126*, 6–14.

Beerkircher, L. R., Cortes, E., & Shivji, M. S. (2002). Characteristics of shark bycatch observed on pelagic longlines off the southeastern United States, 1992–2000. *Marine Fisheries Review*, *64*, 40–49.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B, Statistical Methodology*, *57*, 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bigelow, K. A., Kerstetter, D. W., Dancho, M. G., & Marchetti, J. A. (2012). Catch rates with variable strength circle hooks in the Hawaii-based tuna longline fishery. *Bulletin of Marine Science*, *88*, 425–447. https://doi.org/10.5343/bms.2011.1052

Block, B. A., Teo, S. L. H., Walli, A., Boustany, A., Stokesbury, M. J. W., Farwell, C. J., Weng, K. C., Dewar, H., & Williams, T. D. (2005). Electronic tagging and population structure of Atlantic Bluefin Tuna. *Nature*, *434*, 1121–1127. https://doi.org/10.1038/nature03463

Burns, A. G., & Kerstetter, D. W. (2022). A comparison of circle and J hook performance within the Grenadian pelagic longline fishery. *Caribbean Journal of Science*, *52*, 191–202. https://doi.org/10.18475/cjos.v52i2.a6

Campbell, L. M., & Cornwell, M. L. (2008). Human dimensions of bycatch reduction technology: Current assumptions and directions for future research. *Endangered Species Research*, *5*, 325–334. https://doi.org/10.3354/esr00172

Coelho, R., Santos, M. N., & Amorim, S. (2012). Effects of hook and bait on targeted and bycatch fishes in an equatorial Atlantic pelagic longline fishery. *Bulletin of Marine Science*, *88*, 449–467. https://doi.org/10.5343/bms.2011.1064

Curran, D, & Bigelow, K. (2011). Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery. *Fisheries Research*, *109*, 265–275. https://doi.org/10.1016/j.fishres.2011.02.013

Danylchuk, A. J., Suski, C. D., Mandelman, J. W., Murchie, K. J., Haak, C. R., Brooks, A. M., & Cooke, S. J. (2014). Hooking injury, physiological status and short-term mortality of juvenile Lemon Sharks (*Negaprion brevirostris*) following catch-and-release recreational angling. *Conservation Physiology*, *2*, Article cot036. https://doi.org/10.1093/conphys/cot036

Foster, D. G., Parsons, G. R., Snodgrass, D., & Shah, A. (2015). At-sea factors that affect Yellowfin Tuna grade in the Gulf of Mexico pelagic longline tuna fishery. *Fisheries Research*, *164*, 59–63. https://doi.org/10.1016/j.fishres.2014.10.013

Galuardi, B., Royer, F., Golet, W., Logan, J., Neilson, J., & Lutcavage, M. (2010). Complex migration routes of Atlantic Bluefin Tuna (*Thunnus thynnus*) question current population structure paradigm. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*, 966–976. https://doi.org/10.1139/F10-033

Gilman, E., Chaloupka, M., & Musyl, M. (2018). Effects of pelagic longline hook size on species- and size-selectivity and survival. *Reviews in Fish Biology and Fisheries*, *28*, 417–433. https://doi.org/10.1007/s11160-017-9509-7

Hernández, C. M., Richardson, D. E., Rypina, I. I., Chen, K., Marancik, K. E., Shulzitski, K., & Llopiz, J. K. (2022). Support for the Slope Sea as a major spawning ground for Atlantic Bluefin Tuna: Evidence from larval abundance, growth rates, and particle-tracking simulations. *Canadian Journal of Fisheries and Aquatic Sciences*, *79*, 814–824. https://doi.org/10.1139/cjfas-2020-0444

Kerstetter, D. W., & Graves, J. E. (2006). Effects of circle versus J-style hooks on target and non-target species in a pelagic longline fishery. *Fisheries Research*, *80*, 239–250. https://doi.org/10.1016/j.fishres.2006.03.032

Lima, F. D., Parra, H., Alves, R. B., Santos, M. A. R., Bjorndal, K. A., Bolten, A. B., & Vandeperre, F. (2023). Effects of gear modifications in a North Atlantic pelagic longline fishery: A multiyear study. *PLoS ONE*, *18*, Article e0292727. https://doi.org/10.1371/journal.pone.0292727

Lutcavage, M. E., Brill, R. W., Skomal, G. B., Chase, B. C., Goldstein, J. L., & Tutein, J. (2000). Tracking adult North Atlantic Bluefin Tuna (*Thunnus thynnus*) in the northwestern Atlantic using ultrasonic telemetry. *Marine Biology*, *137*, 347–358. https://doi.org/10.1007/s002270000302

Mantel, N., & Haenszel, W. M. (1959). Statistical aspects of the analysis of data from retrospective studies of disease. *Journal of the National Cancer Institute*, *22*, 719–748. https://doi.org/10.1093/jnci/22.4.719

McLellan, W. A., Arthur, L. H., Mallette, S. D., Thornton, S. W., McAlarney, R. J., Read, A. J., & Pabst, D. A. (2015). Longline hook testing in the mouths of pelagic odontocetes. *ICES Journal of Marine Science*, *72*, 1706–1713. https://doi.org/10.1093/icesjms/fsu181

Menashes, E. H . (2011). *Final environmental assessment, final regulatory impact review, and final regulatory flexibility analysis for a final rule to require the use of weak hooks on pelagic longline vessels in the Gulf of Mexico*. National Oceanic and Atmospheric Administration. https://repository.library.noaa.gov/view/noaa/4106

Mohan, J. A., Jones, E. R., Hendon, J. M., Falterman, B., Boswell, K. M., Hoffmayer, E. R., & Wells, R. J. D. (2020). Capture stress and post-release mortality of Blacktip Sharks in recreational charter fisheries of the Gulf of Mexico. *Conservation Physiology*, *8*, Article coaa041. https://doi.org/10.1093/conphys/coaa041

National Marine Fisheries Service. (2022). *Stock assessment and fisheries evaluation report: Atlantic highly migratory species 2022*. https://www.fisheries.noaa.gov/s3/2023-06/SAFE-Report-062223.pdf

National Oceanic and Atmospheric Administration. (1981). *Atlantic Bluefin Tuna*. Federal Register 46:16(26 January 1981):8012–8015.

National Oceanic and Atmospheric Administration. (2011). *Atlantic highly migratory species; Bluefin Tuna bycatch reduction in the Gulf of Mexico pelagic longline fishery*. Federal Register 76:65(5 April 2011):18653–18661.

National Oceanic and Atmospheric Administration. (2014). *Atlantic highly migratory species; 2006 Consolidated Atlantic Highly Migratory Species (HMS) Fishery Management Plan; Amendment 7*. Federal Register 79:231(2 December 2014):71509–71608.

National Oceanic and Atmospheric Administration. (2016). *Atlantic highly migratory species; Individual Bluefin Quota Program; Inseason transfers*. Federal Register 81:250(29 December 2016):95903–95909.

National Oceanic and Atmospheric Administration. (2020). *Atlantic highly migratory species; Atlantic Bluefin Tuna fisheries; pelagic longline fishery management*. Federal Register 85:64(2 April 2020):18812–18843.

National Oceanic and Atmospheric Administration. (2023). *Taking of marine mammals incidental to commercial fishing operations; amendment to the Atlantic Pelagic Longline Take Reduction Plan*. Federal Register 88:108(6 June 2023):36965–36972.

Orbesen, E. S., Brown, C. A., Snodgrass, D., Serafy, J. E., & Walter, J. F., III. (2019). At-vessel and postrelease mortality rates of Bluefin Tuna (*Thunnus thynnus*) associated with pelagic longline gear in the northern Gulf of Mexico. *U.S. National Marine Fisheries Service Fishery Bulletin*, *117*, 15–23. https://doi.org/10.7755/FB.117.1.3

Orbesen, E. S., Snodgrass, D. G., Shideler, G. S., Brown, C. A., & Walter, J. F. (2017). Diurnal patterns in Gulf of Mexico epipelagic predator interactions with pelagic longline gear: Implications for target species catch rates and bycatch mitigation. *Bulletin of Marine Science*, *93*, 573–589. https://doi.org/10.5343/bms.2016.1008

Pacheco, J., Kerstetter, D., Hazin, F., Hazin, H., Segundo, R., Graves, J., Carvalho, F., & Travassos, P. (2011). A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. *Fisheries Research*, *107*, 39–45. https://doi.org/10.1016/j.fishres.2010.10.003

Richards, W. J. (1976). Spawning of Bluefin Tuna (*Thunnus thynnus*) in the Atlantic Ocean and adjacent seas. *ICCAT Collective Volume of Scientific Papers*, *5*, 267–278.

Richardson, D. E., Marancik, K. E., Guyon, J. R., Lutcavage, M. E., Galuardi, B., Lam, C. H., Walsh, H. J., Wildes, S., Yates, D. A., & Hare, J. A. (2016). Discovery of a spawning ground reveals diverse migration strategies in Atlantic Bluefin Tuna (*Thunnus thynnus*). *Proceedings of the National Academy of Sciences of the United States of America*, *113*, 3299–3304. https://doi.org/10.1073/pnas.1525636113

Rooker, J. R., Secor, D. H., De Metrio, G., Schloesser, R., Block, B. A., & Neilson, J. D. (2008). Natal homing and connectivity in Atlantic Bluefin Tuna populations. *Science*, *322*, 742–744. https://doi.org/10.1126/science.1161473

Rypina, I. I., Chen, K., Hernandez, C. M., Pratt, L. J., & Llopiz, J. K. (2019). Investigating the suitability of the Slope Sea for Atlantic Bluefin Tuna spawning using a high-resolution ocean circulation model. *ICES Journal of Marine Science*, *76*, 1666–1677. https://doi.org/10.1093/icesjms/fsz079

Sales, G., Giffoni, B. B., Fiedler, F. N., Azevedo, V. G., Kotas, J. E., Swimmer, Y., & Bugoni, L. (2010). Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *20*, 428–436. https://doi.org/10.1002/aqc.1106

Scott, M., Cardona, E., Scidmore-Rossing, K., Royer, M., Stahl, J., & Hutchinson, M. (2022). What's the catch? Examining optimal longline fishing gear configurations to minimize negative impacts on non-target species. *Marine Policy*, *143*, Article 105186. https://doi.org/10.1016/j.marpol.2022.105186

Serafy, J. E., Orbesen, E. S., Snodgrass, D. J., Beerkircher, L. R., & Walter, J. F. (2012). Hooking survival of fishes captured by the United States Atlantic pelagic longline fishery: Impact of the 2004 circle hook rule. *Bulletin of Marine Science*, *88*, 605–621. https://doi.org/10.5343/bms.2011.1080

Shivji, M. S., Magnussen, J. E., Beerkircher, L., Hinteregger, G., Lee, D. W., Serafy, J., & Prince, E. D. (2006). Validity, identification, and distribution of the Roundscale Spearfish, *Tetrapturus georgii* (Teleostei: Istiophoridae): Morphological and molecular evidence. *Bulletin of Marine Science*, *79*, 483–491.

Smith, J. A., Tommasi, D., Sweeney, J., Brodie, S., Welch, H., Hazen, E. L., Muhling, B., Stohs, S. M., & Jacox, M. G. (2020). Lost opportunity: Quantifying the dynamic economic impact of time–area fishery closures. *Journal of Applied Ecology*, *57*, 502–513. https://doi.org/10.1111/1365-2664.13565

Smith, M. D., & Wilen, J. E. (2003). Economic impacts of marine reserves: The importance of spatial behavior. *Journal of Environmental Economics and Management*, *46*, 183–206. https://doi.org/10.1016/S0095-0696(03)00024-X

Standing Committee on Research and Statistics. (2021). *Report of the 2021 western Bluefin Tuna stock assessment session*. International Commission for the Conservation of Atlantic Tunas. www.iccat.int/Documents/SCRS/DetRep/WBFT_SA_ENG.pdf

Stokes, L. W., Hataway, D., Epperly, S. P., Shah, A. K., Bergmann, C. E., Watson, J. W., & Higgins, B. M. (2011). Hook ingestion rates in loggerhead sea turtles *Caretta caretta* as a function of animal size, hook size, and bait. *Endangered Species Research*, *14*, 1–11. https://doi.org/10.3354/esr00339

Swimmer, Y., Gutierrez, A., Bigelow, K., Barceló, C., Schroeder, B., Keene, K., Shattenkirk, K., & Foster, D. G. (2017). Sea turtle bycatch mitigation in U.S. longline fisheries. *Frontiers in Marine Science*, *4*, Article 260. https://doi.org/10.3389/fmars.2017.00260

Teo, S. L. H., & Block, B. A. (2010). Comparative influence of ocean conditions on Yellowfin and Atlantic Bluefin Tuna catch from longlines in the Gulf of Mexico. *PLoS ONE*, *5*, Article e10756. https://doi.org/10.1371/journal.pone.0010756

Teo, S. L. H., Boustany, A., Dewar, H., Stokesbury, M. J. W., Weng, K. C., Beemer, S., Seitz, A. C., Farwell, C. J., Prince, E. D., & Block, B. A. (2007). Annual migrations, diving behavior, and thermal biology of Atlantic Bluefin Tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. *Marine Biology*, *151*, 1–18. https://doi.org/10.1007/s00227-006-0447-5

Wise, J. P., & Davis, C. W. (1973). *Seasonal distribution of tunas and billfishes in the Atlantic* (Technical Report NMFS SSRF 662). National Oceanic and Atmospheric Administration.