Version of Record: https://www.sciencedirect.com/science/article/pii/S0308597X15003863
Manuscript_40615d44b584071451b7c4820cb4c66e

Influence of Hook Type on Catch of Commercial and Bycatch Species in an Atlantic Tuna Fishery

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Running page head: Circle hooks in deep set longline fisheries

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Abstract

Experimental sets were conducted on a Taiwanese deep set longline fishing vessel operating in the tropical Atlantic Ocean to evaluate the effects of relatively wide circle hooks vs Japanese tuna hooks with respect to catch rates of both target and incidental species. On circle hooks there were significantly higher catch rates of bigeye tuna (*Thunnus obesus*), yellowfin tuna (*T. albacares*), swordfish (*Xiphias gladius*) and blue sharks (*Prionace glauca*) as compared to tuna hooks. Significantly higher rates of albacore (*T. alalunga*) and longbill spearfish (*Tetrapterus pfluegeri*) were caught on Japanese tuna hooks as compared to circle hooks. Overall, 55 sea turtles were incidentally captured, most (n=47) of which were leatherback turtles (*Dermochelys coriacea),* and capture rates were similar between hook type. Immediate survival rates (percentage alive) when landed were statistically similar for all major target fish species and sea turtles independent of hook type. Most (64%) sea turtles were hooked on the first and second branchlines closest to the float, which are the shallowest hooks deployed on a longline. Lengths of six retained species were compared between hook types. Of these, swordfish was the only species to show a significant difference in length by hook type, which were significantly larger on circle hooks compared to tuna hooks. Additional incentives to use circle hooks would be the increased catch rate in targeted bigeye tuna over traditional Japanese tuna hooks. This international collaboration was initiated in direct response to regional fisheries management organization recommendations that encourage member countries to conduct experiments aimed to identify means to reduce bycatch in longline fishing gear. Information presented may be useful for managers in developing international fisheries policies that aim to balance increases in commercial fishery revenue and endangered species protection.

Key words: circle hook, tuna, sea turtle bycatch, deep set longline, regional fisheries management organization.

1. Introduction

The incidental capture of non-target species occurs in a broad range of fisheries, including trawl gear, gillnets, purse seines and longlines and is of global concern [1]. Much attention has been directed at the deleterious effects of pelagic longline fishing (PLL), a gear type present in all the world's oceans that has been associated with high incidental catch and mortality of numerous incidentally-captured species [2, 3]. Pelagic longline gear is generally set "shallow" when targeting swordfish (*Xiphias gladius)* while deeper lines are generally set when targeting tunas (*Thunnus spp.),* though there may be regional variations. The incidental catches of "non target" species can be divided into two types: incidental yet retained for either commercial value or utilization (eg., used as bait), or discarded as bycatch. Bycaught species are those that are generally released to sea given their lack of commercial value or due to their protection under the law, and thus species considered bycatch differs regionally. Marine mammals, sea birds, sea turtles and certain finfish are considered bycatch as they are protected under various national and international laws.

Extensive research has been undertaken to identify means to maximize capture of target species while minimizing the impacts to incidental captures, especially those that are protected under various laws. The likelihood of catching specific species is largely dependent on a suite of environmental and operational factors, such as seasonality, temperature, bait type, hook depth, etc. In PLL, important variables to consider can include specifics such as hook shape, hook size, bait type, gear depth, time of longline set and retrieval, and fishing location [3, 12, 13]. Recent research has identified a potential conservation value to the use of circle hooks, which is a fish hook whereby the point of the hook curves inward perpendicular to the shank (Figure 1), leaving the point less exposed compared to other hook types [4-6]. It is presumed that this shape results in failed attempts to digest the baited hook and can also reduce the frequency of "foul-hooking" that results when an animal is incidentally snagged by an exposed hook point. The shape differences between circle hooks and other tuna hooks is likely a contributing factor to species' catchability given that circle hooks are generally considerably wider in their width (A) dimension (Figure 1).

[FIG 1 here}

It is widely believed that circle hooks may result in less serious injury to both fishes and bycatch species due to the increased probability of external hooking on the body as compared to more frequent internal ingestion of narrower J-hooks or tuna hooks [7]. External hookings are generally considered to result in less severe injury and with a higher likelihood of post-release survival as compared to damage caused by internal ingestions. The potential for higher rates of survival is especially valuable for discarded or bycatch species that are released to sea with the expectation of high rates of survival, thereby minimizing population-level effects from the fisheries interactions.

Of particular concern regarding incidental captures is that of sea turtle bycatch. All sea turtle species are listed as endangered or threatened and are protected under both Taiwanese and U.S. laws. Numerous studies have shown relatively high rates of sea turtle captures in longline gear in all major ocean basins including the Atlantic Ocean[4, 8, 9], Pacific Ocean [10-13], and Mediterranean Sea [14, 15]. Given the potentially negative impacts on sea turtle populations due to capture in longline fisheries, in particular leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) turtles, there has been extensive research toward identifying mitigation methods to reduce rates of incidental capture and increase the probability of survival in the event of a fisheries interaction. The use of relatively large (wide) circle hooks in combination with finfish bait has been shown to significantly reduce the frequency of sea turtle hooking compared to J-shaped hooks or tuna hooks with squid bait in a number of longline fisheries [4, 16, 17].

Based on the numerous conservation values attributed to circle hooks, particularly in shallow-set swordfish-targeted fisheries, the United States (U.S) has mandated use of circle hooks and finfish as bait in shallow set longline fisheries in the Pacific Ocean. U.S. fisheries targeting highly migratory species in the Atlantic and Gulf of Mexico are required to use circle hooks but not necessarily fish bait. More information on U.S. fishing regulations aimed to protect sea turtles can be found at www.nmfs.noaa.gov/pr/species/turtles/regulations.htm. Internationally, some regional fisheries management organizations (RFMOs) encourage circle hook use in shallow set longline fisheries (e.g., Western and Central Pacific Fisheries Commission Conservation and Management Measure 2008-03). The majority of tuna RFMOs have adopted measures requesting members to conduct experimental research on circle hooks for their longline fleets (e.g., Inter-American Tropical Tuna Commission Resolution 07-03).

Adoption of relatively wide circle hook use may be hindered by concerns that use of circle hooks may result in reduced capture rates of target species, in particular swordfish, which has been previously reported [4, 7, 16]. There have also been reports of similar catch rates of swordfish between circle hooks and traditional hooks in experimental fisheries [18, 31]. Despite efforts to standardize even at the level of terminal gear, the variability in findings suggest the importance of factors such as bait type as well as hook dimensions in species' catchabilities. Unlike the numerous findings of reduced capture of swordfish on circle hooks, however, there are consistent findings that capture rates for tuna species are often higher on circle hooks compared to J and tuna hooks [4, 8, 18].

Despite extensive research aimed to determine the conservation benefit of circle hook use in shallow set longline fisheries, there is limited information on how hook shape influences capture rates of bycatch species in deep-set tuna longline fleets. In the case of sea turtles, it is well established that capture rates of sea turtles caught on deep set longline gear are substantially lower than on shallower set hooks [19, 20], which is consistent with the relatively shallow distribution of sea turtles throughout their ranges [21-23]. However, the depth of deep set gear often results in a high probability of mortality due to drowning, as seen in relatively deep dwelling olive ridley turtles captured in a North Pacific Ocean longline fishery [24]. It remains unclear how circle hook use in a deep set fishery affects the capture rates of bycatch species.

This collaborative international research was conducted in direct response to RFMO recommendations that encourage member countries to conduct experiments aimed to identify means to reduce bycatch in longline fishing gear. Of the three Taiwanese longline fleets operating in the Atlantic Ocean, the bigeye tuna fleet in the tropical areas has the highest rate of sea turtle captures compared to the albacore (*Thunnus alalunga*) fleets in the north and south Atlantic [25]. The primary goals of this study were to better understand the potential conservation value of using circle hooks in a deep set tuna fishery. Specifically we looked at relationships between hook type on catch composition of target and non- target species, the rates of immediate survival (percentage of animals alive at gear retrieval–haul back), as well as catch sizes as a function of hook type. This work represents a unique collaboration between the U.S. and Taiwanese governments. Working in conjunction with industry, this study compared the catch rates of target species, such as bigeye tuna (*T. obesus*), yellowfin tuna *(T. albacares)*, swordfish, and bycatch (discarded) species (e.g., sea turtles) using 18/0 circle hooks and a traditional Japanese style tuna hook (4.2 sun) in a deep set longline fishery in the tropical Atlantic Ocean.

2. Materials and Methods

2.1 Study region and fishing gear

This study was conducted on a Taiwanese commercial bigeye tuna longline fishing vessel (51.65 m, GRT 496 tons). The vessel operated in the tropics between 2° and 12° S latitude and 17.0° and 26.0° W longitude during September 2012 to May 2013. Fishing gear consisted of a standard monofilament mainline 4 mm in diameter with 16-17 branchlines deployed between floats. Each branchline was ~46 m in length. The components of the branchline, listed in order from the snap to the hook, were ~1.5 m of white three strand nylon, 21 m of 2.1 mm monofilament, 13 m of 1.8 mm monofilament, 4 m of bloodline and 6 m of 1.8 mm monofilament. Each segment was separated by a barrel swivel. Branchlines were marked at the longline snap to assist with identifying the terminal hook type. The length of the floatline was 45 m.

A size 18/0 stainless steel Korean-made circle hook with a 10° offset was used as the experimental hook and a Japanese tuna hook with a minimal offset and measured as 4.2 sun was used as a control (Figure 2). Circle hooks measured larger in gape (2.8 vs. 2.7 cm), minimum width (5.6 cm vs. 3.5 cm), and maximum length (8.7 cm vs. 7.0 cm) than Japanese tuna hooks. Both hook types had rings and were sequentially alternated in a 1:1 ratio along the length of the experimental portion of the mainline.

Three species of whole finfish were used as bait throughout the experiment: milkfish (*Chanos chanos*), mackerel (family Scombridae), and sardine (family Clupeidae), which were comparable in size (182-220 g). The average weight of the milkfish, mackerel, and sardine was ~200 g. Baiting techniques remained consistent throughout the experiment and are described as single-threaded.

Approximately 3500 hooks were deployed on each set, and the initial ~2040 hooks were observed in this experiment. Gear was deployed at approximately 0400~0600 hours and soaked 5-7 hours prior to initiating retrieval. Gear haul back started at approximately 1200-1400 hours and lasted for 15-17 hours.

2.2 Sampling design and data collection

A power analysis was used to estimate the minimum number of sets (200) in order to detect a difference in bigeye tuna capture rates between hook type with alpha=0.1 and beta=0.2 or power=80%, assuming a two-sided hypothesis, with the null hypothesis being no difference in catch rates.

For each set, the observer recorded operational factors, such as each set's initial deployment time and location (latitude and longitude), number of hooks deployed, bait types for each hook position, and environmental variables, including sea surface temperature (SST). Catch composition by hook type was recorded for all target and non-target species. Whenever possible, catch composition information included the number of individuals by species retained, discarded dead, and released alive by hook type and hook position between floats. Additionally, the weight of retained catch (kg) and evidence of depredation by sharks, cetaceans, and unknown animals were also recorded.

Additional data were collected on incidentally captured sea turtles, including hook and bait type (whenever possible), condition when landed and released (dead/alive), type of capture (hooked or entangled), hooking location (e.g., flippers, mouth, beak [sea turtles only]), turtle size (e.g., carapace curve length [CCL]), and, if possible, sex. Turtles were considered "externally" hooked when the hook was observed in the front or rear flippers, shoulder/armpit, beak and neck and "internally" hooked when the hook was lodged in the beak (upper and lower jaw), mouth, tongue, roof of mouth, and mouth-jaw joint.

Hard-shelled turtles were landed on board and, when appropriate, hooks were removed by the observer using NOAA-approved methods [26]. Due to the large size of leatherback turtles (up to ~ 700 kg), most were immediately released by cutting the branch line. As such, it was not always possible to determine if turtles had also been hooked in addition to entanglement. In a few cases, leatherback turtles were landed on board using a fabricated harness to allow for hook removal and line disentanglement as well as body measurements prior to release.

2.3 Data analysis

Due to the non-normal distribution of catch data, a randomization test was used to assess catch differences between hook types, as described in a review on experimental design and statistical methods for longline fisheries [27]. The null hypothesis was that there would be no difference in catch between paired hook types. The test statistic (*S*) was the mean difference in catch between paired circle hooks and tuna hooks by set. Data were randomized, re-sampled 10,000 times, and scored for whether or not the re-sampled *S* value was equal to or greater than the observed *S* value (R Development Core Team 2008), version 2.7.2 for Linux). Randomization tests provide a measure of the strength of evidence against a null hypothesis [28]. T-tests were used to compare potential differences in mean lengths of fish captured, and odds ratio analyses were used to assess potential differences in the proportion of animals released dead or alive.

3. Results

A total of 200 sets were conducted with a mean number of 2,672 (± SD=457) hooks per set, representing a total of 407,677 observed hooks. Throughout the experiment, predominant sea surface temperatures (SST) ranged between 26°C and 28°C.

3.1 Catch Composition

3.1.1 Fish, Elasmobranchs

In total, 38 fish species were caught, of which six had greater than 100 individuals caught per species. These included commercially valuable tuna species, including bigeye, yellowfin, and albacore, as well as swordfish, as well as longbill spearfish (*Tetrapterus pfluegeri)* and blue shark (*Prionace glauca)*, both of which are generally discarded as bycatch. Catch rates of bigeye tuna (p=0.0002), blue shark (p=0.0209), swordfish (p=0.0001), and yellowfin tuna (p=0.0449) were statistically higher on circle hooks compared to Japanese tuna hooks. Catch rates of albacore (p=0.0100) and spearfish (p=0.0097) were significantly higher on Japanese tuna hooks compared to circle hooks (Table 1).

[TABLE 1]

3.1.2 Sea Turtles

In total, 55 turtles were captured, including 18 caught on circle hooks, 18 on Japanese tuna hooks, and 19 entangled either in the mainline (n=12), branch line (n=2) or floatline (n=5). Of the 18 hooked sea turtles, half (n=9) were caught on each hook type, resulting in a shared CPUE of 0.09 sea turtles captured per 1,000 hooks for both circle and tuna hooks. By species, leatherback turtles represented the highest proportion of turtle bycatch by species (86%, n=47), followed by olive ridley (13%, n=7) and one loggerhead turtle (2%, n=1). The single loggerhead turtle was caught on a Japanese tuna hook, and the number of leatherback and olive ridley turtle captures were evenly distributed by hook type and entanglement (Table 2).

Given that entangled turtles were omitted from comparative hook analysis, data presented includes 29 hooked leatherbacks, 6 olive ridleys and 1 loggerhead turtle. Catch rates of combined sea turtle species (n=36) were similar between hook types (p=1.000; Table 2). Of the 19 turtles that were entangled, 18 were leatherbacks.

[TABLE 2]

Of the 200 sets, 30 sets (15%) caught at least one sea turtle, and no turtles were caught on 170 sets. The highest bycatch incident occurred when four turtles were caught on a single set (two hooked and two entangled). Overall, multiple captures occurred on 12 sets, representing 6% of total sets. All hooked turtles were captured on the 4 shallowest hooks nearest to the floats, and 64% (23 of 36) were captured on the first two hooks closest to the floats. The locations of turtle captures in relation to effort (number of hooks set) are in figure 3.

[FIG 3 here]

The type of hooking, either external (eg. flipper) or internal (eg., hook swallowed), was also recorded for sea turtles for each hook type and is reported in Table 3.

[TABLE 3 here]

3.2 Rates of Survival and Hook Type:

Immediate survival rates (percentage alive) when landed were statistically similar for all major target fish species independent of hook type ($p>0.35$ all species; Table 4). Table 4 reports the percentage of immediate survival for all sea turtles brought on board, which is similar among species caught on each hook type. The percentage of leatherback turtles alive when landed was slightly higher on circle hooks compared to tuna hooks (87% vs 71%), but this was not statistically significant ($p=0.38$). The majority (66%) of leatherback turtles were released alive. Of the 16 dead leatherback turtles, 10 (63%) had been entangled in the line. All ($n=8$) hard-shelled turtles (loggerhead and olive ridley) were dead when landed.

[TABLE 4 here]

3.3 Catch Sizes

Lengths of six retained species were compared between hook types. Of these, swordfish was the only species to show a significant difference in length by hook type ($p=0.004$), which were significantly larger on circle hooks compared to tuna hooks (Table 5). Leatherback turtles captured on hooks ranged in size from 92 to 151 cm CCL (average = 118.9 cm for tuna hooks, 124.0 cm for circle hooks). Olive ridley turtles ranged in size from 56 cm to 65 cm (average = 58.3 cm for Japanese tuna hooks, 62.3 cm for circle hooks). The loggerhead turtle was 78 cm (Table 5).

[TABLE 5 here]

4. Discussion

Capture rates of commercially valuable bigeye tuna, swordfish and yellowfin tuna were higher on circle hooks compared to Japanese style tuna hooks, while higher catch rates of albacore were observed on Japanese tuna hooks compared to circle hooks. With regard to bycaught and discarded species, blue sharks were caught with greater frequency on circle hooks and longbill spearfish were caught with greater frequency on Japanese tuna hooks. Despite expectations to the contrary, there were no differences in sea turtle catch rates nor in the immediate survival of any species between hook types. There were no detectable differences in the size distribution of any species between hook types except for swordfish, which were significantly larger on circle hooks.

Hook type has shown inconsistent results with regards to catch composition, likely due to difficulties isolating explanatory variables. For example, aspects of the gear and fishing operation play large roles in influencing catch composition and abundance, but the relative roles of each parameter remain largely uncertain. Important covariates to consider include hook shape, hook size, bait type (e.g., squid vs. fish), ring presence, degree of hook offset, baiting technique, gear depth, time of longline set and retrieval, fishing location, etc. The term hook shape is used lightly as it often only implies the relative position of the point with respect to the hook shank. However, by definition, the rounding of the hook also results in a wider hook, which must also be considered. This study adds to the growing body of literature on how gear can affect catch composition, which is essential to improve the accuracy of stock assessment models as well as measures aimed to protect threatened and endangered species.

4.1 Effects of circle hooks on commercial species catch

The observed higher catch rate of targeted bigeye tuna on circle hooks compared to tuna hooks is consistent with similar experimental and commercial deep set fisheries data [4, 8, 18, 29]. The increased capture rate of yellowfin and albacore on circle hooks in a similar pelagic longline fishery in the Atlantic ocean was also observed in earlier studies ([2, 30, 31]). While higher rates of immediate survival have been associated with tunas caught on circle hooks [31], this study found only a slightly higher rate of bigeye tuna immediate survival on circle hooks, which suggests the potential for increased fish quality and market value [32]. Based upon findings from numerous studies, and since the time of this experiment, the authors are aware that many tuna fishers from both Taiwan and the United States have voluntarily replaced traditional tuna or J-hooks with circle hooks.

This study found a significantly higher catch rate of bigeye tuna and swordfish on circle hooks compared to tuna hooks, which was unexpected due to previously reported similar [31] or lower catch rates of swordfish by circle hooks [4, 8, 15, 18]. We speculate that this higher rate of retention in tunas may be the result of a relatively wider circle hook that reduces premature dehooking. Watson and colleagues [4], however, reported that that use of fish bait (vs. squid) could offset the loss (19% by weight) of swordfish caught on circle hooks compared to J hooks, hence U.S. federal regulations allow for modifications regarding hook type and bait to balance fisheries and conservation needs [17]. Considering that bigeye tuna is the target species for this fleet, fishermen may be more likely to adopt circle hook use to replace traditional Japanese hooks.

This may be the first report of a Japanese tuna hook associated with statistically higher captures of albacore as compared to circle hooks. For most commercial species in this study, catch rates were similar between hook types.

4.2 Effects of hook type on bycatch species

Recent metadata analyses [33, 34] were conducted of published records in order to elucidate the potential value of circle hook use as a tool for shark conservation in pelagic longline fisheries. Godin and colleagues [33] found that circle hooks did not have a major effect on shark catch rates across species examined, while Gilman and colleagues [34] found higher catch rates associated with wider circle hooks in nearly all elasmobranch species, with the exception of more variable responses within two species, blue and shortfin mako sharks (*Isurus oxyrinchus*). In our study, circle hooks were associated with a higher capture rate of blue sharks, a finding that differs from some studies (e.g., [33, 35, 36], yet is similar to findings in several other studies [4, 8, 34]. In both metanalyses [33,34], sharks captured on wider circle hooks were associated with a higher rate of at-vessel survival as compared to those caught on narrow J-hooks [33, 34]. This was not found in our study, where the percentage of sharks landed on board alive was similar between hook types, a finding observed previously [31]. In addition to hook shape, factors such as bait type, leader material, shark species and size are all contributing explanatory variables that can influence both species' capture risk as well as probability of immediate survival [34].

This study found the longbill spearfish, a relatively small somewhat rare istiophorid billfish found in the Atlantic Ocean and adjacent seas, was associated with higher catch rates on Japanese tuna hooks. Little is apparently known about this species, yet two animals tagged in the Atlantic Ocean in 2004 [37] were found to spend the majority of their time in temperatures between 22 ºC –26 ºC within the top 150m, and with the majority of the time at depths < 25m. Based upon the fishes' depth utilization data, the authors postulate that bycatch in deep-set longline gear, as in this study, occurs primarily at set and retrieval of the gear [37].

4.3 Effects of hook type on sea turtles

Deep set longline fishing generally has rates of sea turtle capture an order of magnitude lower than shallow set longline fishing [3, 19, 21]. In addition to hook depth, there are also operational differences, such as daytime vs. night time setting, soak time, bait type, etc., all of which can influence overall catch composition. In this study on a Taiwanese vessel, baited hooks were set deep to target deep-foraging species. By setting the longline deep, sea turtle capture rates were relatively low, likely because the majority of the gear remained beyond the depth range typically occupied by turtles. The nature of entanglement interactions, particularly with leatherback turtles, precluded the ability to determine the depth of the initial entanglement, but it is highly plausible that these interactions occurred during haulback or setting when gear remains at the surface.

Use of relatively wider circle hooks in this study was not associated with fewer sea turtles captured. This finding was surprising given previous reports that use of circle hooks significantly reduced capture rates of leatherback turtles in a deep set fishery in the South Atlantic Ocean [31]. Circle hooks were also associated with reduced capture rates of both leatherback and hard-shell turtles compared to traditional hooks in shallow-set pelagic longline fisheries [4, 8, 15]. In addition to a relatively low capture rate of sea turtles in this study, the majority of the turtles, leatherbacks, were entangled in the line rather than caught on the hook. It has been proposed that leatherback turtles may be drawn into the vicinity of longline gear by lightsticks attached to branchlines [38], however this theory has never been empirically confirmed, largely due to limited observations of fishing in the absence of lightsticks for comparative purposes.

Fossette and colleagues [39] recently identified regions of susceptibility for leatherbacks in longline fisheries the Atlantic Ocean by integrating spatiotemporal distribution and habitat use by tracking animals with satellite transmitters between reproductive seasons and overlaid with fisheries efforts. It is likely that the leatherbacks encountered in this study were in a migratory South Atlantic corridor between their nesting sites in Gabon to South Atlantic breeding grounds, which would occur during January–March. Leatherback turtle interactions in this study corroborate the identified high-use areas, such as those occurring from 20ºS to 45ºS latitude, and the prediction for high susceptibility of leatherback turtles to longline fishing gear in the equatorial central Atlantic [39].

This study corroborated previous studies that have shown that leatherback sea turtles are most often foul hooked or entangled in line and that hard-shelled turtles are more likely to bite baited hooks [4, 8, 40]. The immediate survival rate was similar for all sea turtle species independent of hook type, which is similar to previous reports [31]. Post-release rates of mortality were not investigated in this study.

Relatively few hard shelled turtles were captured, with the majority being olive ridley turtles, which was predictable given that olive ridley turtle populations are believed to be the most abundant of any species of sea turtles. Also the depth of the baited hooks and the temperature of the associated water temperatures are similar to previously defined habitat for olive ridley turtles in the North Pacific Ocean. Relatively little is known about the movements of olive ridley turtles in this general oceanic area [41], although nesting is known to occur throughout the west coast of Africa between Guinea Bissau and Angola[42]. The region is particularly productive given the convergence of the northern Angolan current with the relatively cool Benguela current from the south, perhaps creating ideal forage habitat [43]. Pikesley and colleagues [43] observed that post-nesting females from Gabon and Angola foraged within oceanic waters where water depths were < 2000 m, with highest densities of olive ridley associated with oceanic fronts within the Angolan Exclusive Economic Zone [43]. Previously described as generalist feeders on fish, molluscs, and crustaceans [44], [45] found that oceanic olive ridley prey items included predominantly subsurface pyrosomes (*Pyrosoma atlantica*) and salps (Salpidea) as well as surface-associated organisms, such as Janthina *sp.* and cowfish (*Lactoria diaphana*), rendering them vulnerable to capture in fisheries that center on highly productive areas, as in this study.

4.4 Influence of hook depth on sea turtle interaction rates

Most (64%) sea turtles were hooked on the first and second branchlines closest to the float, which are the shallowest hooks deployed on a longline. These observations suggest that in deep set longline gear, the type of hook and bait may have limited impact on reducing the number of sea turtles captured. Rather, hook depth may be the most important explanatory variable. All sea turtle species, including leatherback turtles, spend the majority of their time in relatively shallow water, with loggerhead and olive ridley turtles observed to spend 90%

and 60% within the top 40 m, respectively [23, 45]. Despite the physiological capability of leatherback turtles to dive >1000 m, most dives are less than 150 m [46, 47].

As a conservation approach, these shallow hooks could be eliminated from the gear, which has been proposed [21] and tested [3]. In this scenario, the shallowest hook in a deep set fishery would likely remain below ~ 100 m, thereby eliminating capture of epi-pelagic species remaining near the surface at night, coinciding with night time fishing effort. In this study, elimination of the two hooks closest to the float would have resulted in only a ~3% and ~5% loss of commercially valuable bigeye tuna and swordfish capture, respectively. However, albacore capture would have decreased by ~15% and yellowfin tuna by ~52%, thereby suggesting significant economic loss to the fishery with this modification. Beverly and colleagues [3] found that experimental sets with hooks deeper than 100 m in a Hawaii-based tuna fishery had similar catch rates of bigeye tuna compared to control sets, but lower catch rates of species with high market value, such as marlins, dolphinfish (*Coryphaena hippurus*), and wahoo (*Acanthocybium solandri)*. The conservation value of eliminating shallow hooks could be very high, and could be evaluated in terms of revenue loss, as analyzed in [48].

4.5 Influence of bait on sea turtle interactions

Although three species of fish were used as bait throughout the experiment, the results of a number of studies suggest that the use of whole finfish as opposed to squid bait may have resulted in fewer sea turtles captured [4, 40, 49]. For statistical purposes, one species of finfish would have been preferred over the three. However, the long duration of the trips and the nature of the re-supply of the vessel made it unfeasible for the experiment to be conducted using one bait type.

The use of fish bait in this study was likely a contributing factor in the absence of a significant hook effect regarding leatherback sea turtles, which were primarily foul-hooked. Mitigation methods that minimize the exposure of the hook point appear to be effective in reducing captures by foul hooking. Circle hooks have been shown to reduce foul hooking due to the fact that the point of the hook curves inward perpendicular to the shank, leaving the point less exposed compared to J style hooks [4, 5]. Additionally, [4] found that use of large fish bait has also been shown to be effective in reducing the incidence of foul hooking of leatherbacks with J hooks, likely due to a shielding effect of the hook point by the fish bait. However, Foster and colleagues [50] report that the sum effect of the two mitigation techniques (circle hooks and fish bait) when combined is not cumulative. In that study, both 18/0 circle hooks with squid bait and 9/0 J hooks with mackerel bait significantly reduced the catch rate of leatherback sea turtles by 66% and 76% respectively, compared to 9/0 J hooks with squid bait. When the two experimental treatments were combined (i.e., 18/0 circle hook with mackerel bait) the 63% observed reduction was comparable to the performance of each treatment when tested independently. It is therefore likely that the leatherback sea turtle results in the current study were due to shielding of the Japanese tuna hook point by fish bait, which likely offset the mitigation benefit of the curved point of the circle hook in reducing foul hooking.

4.6.Perception of Circle Hooks

Regarding acceptability of circle hooks, comments by the Taiwanese captain and crew suggest that the hardness of the stainless steel circle hooks make them more difficult to re-shape once bent, resulting in a higher replacement rate compared to the tuna hooks. Additionally, the replaced hooks cannot be reused and repaired by regular methods. On the other hand, the crew believed that an advantage of circle hooks over traditional Japanese tuna hooks was their improved ability to retain caught fish since they are not easily de-hooked. From a conservation perspective, this may also result in increased injuries associated with efforts to de-hook and release incidentally caught fish, thereby possibly reducing their post-release survival.

5. Conclusions

This collaborative international research was conducted in direct response to RFMO recommendations that encourage member countries to conduct experiments aimed to identify new and confirm known means to reduce sea turtle bycatch in longline fishing gear. Specifically, FAO guidelines have identified the following methods to effectively reduce sea turtle mortality associated with longline fishing gear: 1) Use of large circle hooks with no greater than a 10 degree offset, combined with whole fish bait; 2) Arrangement of gear configuration and setting so that hooks remain active only at depths beyond the vertical range of sea turtle interaction; and 3) Retrieval of longline gear earlier in the day thereby reducing soak time of hooks [1]. Yet additional work remains to predict and avoid abundance of sea turtles in fisheries hot spots, primarily with improved communication.

The results of this study suggest the need for additional biological and economic analyses to explore the potential to eliminate shallow hooks in a deep set fishery in an effort to balance conservation with commercial fishing. This may involve further understanding of market value by fish species as well as the economic costs of capturing bycatch species.

Acknowledgments

This project was funded by the United States National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) through a monetary arrangement with the International Convention for the Conservation of Atlantic Tunas (ICCAT). The experiment was conducted and implemented by the Taiwan Fisheries Agency with technical expertise provided by NMFS. Appreciation is extended to Mr. Tsai, the fisheries observer, for his efforts on board the fishing vessel to collect this valuable information, the Fisheries Agency for providing the relevant bycatch database, and to the Taiwan Tuna Association and Yuan-Hung Company for their assistance. Additional gratitude is extended to Kim Dietrich who provided the observer training and to Daniel Curran of NMFS PIFSC who assisted with gear configurations as well as valuable editorial contributions.

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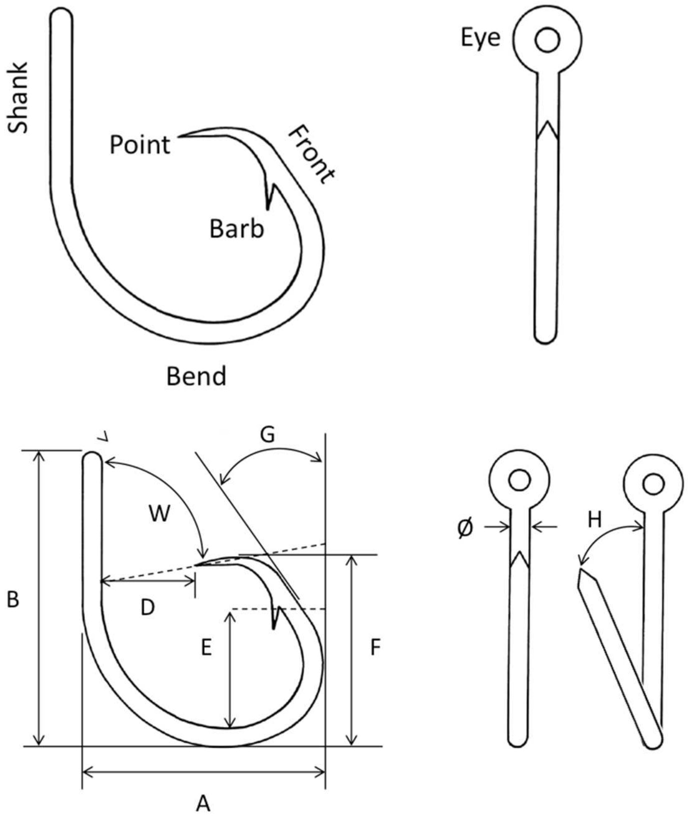
Figure 1. Anatomy of a circle hook. Basic components (upper panel) and measurements (lower panel): minimum width (A); straight total length (B); gape (D); throat (E); front length (F); point angle (W); front angle (G); offset angle (H).

Figure 2. Dimensions of tuna hook (left) and circle hook (right) used in the experiment.

Figure 3. Fishing locations (5^{o} x 5^{o}) and sea turtle bycatch distribution by species and fishing effort.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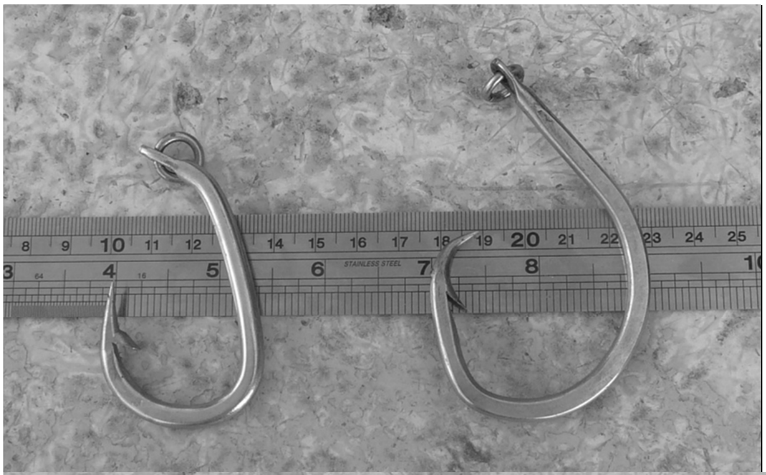
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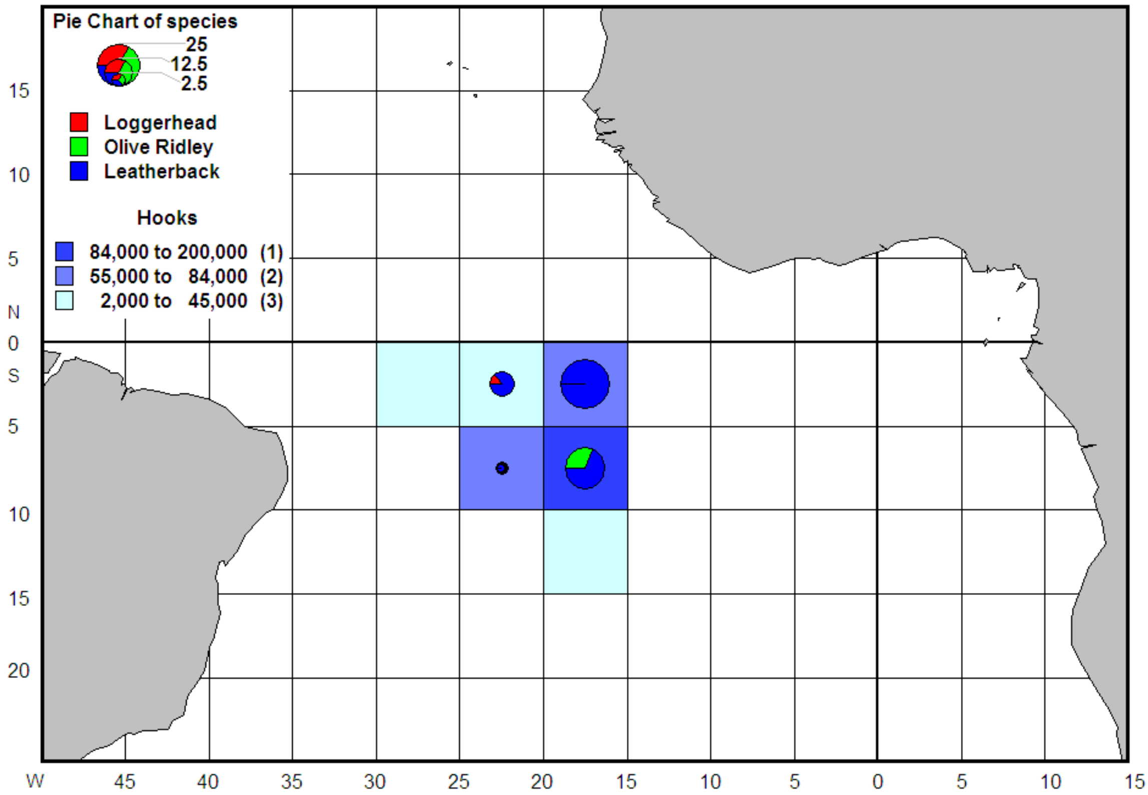

Pie Chart of species
25
12.5
2.5
Loggerhead
Olive Ridley
Leatherback
Hooks
84,000 to 200,000 (1)
55,000 to 84,000 (2)
2,000 to 45,000 (3)
15
10
5
N
0
S
5
10
15
20
W
45
40
35
30
25
20
15
10
5
0
5
10
15

Table 1. Catch composition by hook type. CPUE = catch per unit effort, where catch = number of individuals captured.

Hook type	Circle hooks		Japanese Tuna hooks		Randomization test
Species	Total number	Average CPUE (#/1000 hooks)	Total number	Average CPUE (#/1000 hooks)	P-value
Bigeye tuna	1155	5.66	945	4.63	0.0002
Yellowfin tuna	65	0.32	41	0.20	0.0449
Albacore	67	0.33	103	0.50	0.0009
Swordfish	341	1.67	220	1.08	0.0001
Longbill spearfish	115	0.56	146	0.72	0.0097
Blue shark	611	3.00	564	2.76	0.0209
Sea turtles	18	0.09	18	0.09	1.0000

Table 2. Sea turtle captures by hook type. Number of turtles dead when landed are noted in parentheses.

Hook Type	Loggerhead	Olive ridley	Leatherback	Total
Japanese Tuna	1 (1)	3 (3)	14 (4)	18 (8)
Circle	0	3 (3)	15 (2)	18 (5)
Entangled	0	1 (1)	18 (10)	19 (11)
Sum	1 (1)	7 (7)	47 (16)	55 (24)

Table 3. Sea turtle anatomical hooking location by hook type. Note: olive ridley=LO. All others were leatherback with the exception of one loggerhead.

	Tuna hook	Circle hook	Entangled	Total
Not hooked			19 (1 LO)	19
External	11	11		22
Internal	5	6		11
Unknown hooking location	2	1		3
Total	18	18	19	55

Table 4. Effect of hook type on immediate survival of animal upon being boated.

Species	Percent survival		Odds ratio (P-value)
	Tuna hook	Circle hook	

Leatherback turtle	71.4	86.7	0.38 (0.38)
Blue shark	69.0	69.1	0.99 (1.00)
Bigeye tuna	42.0	46.0	0.85 (0.70)
Albacore	22.3	31.3	0.63 (0.20)
Yellowfin tuna	26.8	29.2	0.88 (0.82)
Swordfish	15.0	15.0	1.00 (1.00)
Longbill spearfish	12.3	13.9	0.87 (0.72)
Loggerhead turtle	0.0	N/A	N/A
Olive ridley turtle	0.0	0.0	1.00

Table 5. Catch size composition (cm) by species and hook type. CCL=curved carapace length (cm); FL=fork length; LL=lower fork length. *=Statistically different.

	Tuna hooks		Circle hooks		P value
Species	Average (±SE)	Range (cm)	Average (±SE)	Range (cm)	
Sea Turtles (CCL)					
Loggerhead	78.00	78- 78			
Olive ridley	58.33±3.21	56- 62	62.33±3.06	59 ~65	
Leatherback	118.92±19.79	93- 151	124.00±15.68	92 ~147	
Tuna (FL)					
Albacore	104.14±4.32	92- 126	103.95±3.88	96 ~111	0.777
Bigeye tuna	134.51±23.54	76- 193	135.64±23.23	76 ~192	0.285
Yellowfin tuna	139.73±13.97	103- 164	139.68±13.20	117 ~170	0.983
Billfish (LL)					
Swordfish	164.37±23.59	113-248	170.90±25.09	76 ~265	0.004*
Longbill Spearfish	161.67±10.07	131-164	161.21±17.87	117 ~170	0.815
Sharks (FL)					
Blue shark	183.26±17.54	70- 232	183.85±16.91	70 ~255	0.566