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ORIGINAL PAPER

Sustainable fishing gear: the case of modified circle hooks in a Costa Rican longline fishery

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Abstract Our research aims to identify longline fishing gear modifications that can improve fishing selectivity and reduce incidental capture of non-target species. Catch rates and anatomical hook locations (AHL) were compared when using a 14/0 standard "control" circle hook with a 0° offset and an experimental "appendage" hook in a Costa Rican longline fishery. With the appendage, the maximum dimension of the appendage hook was increased by 10% and the minimum dimension of the hook by 19%. A total of 1,811 marine animals were captured during five fishing trips. By taxonomic groups, sea turtles represented the largest total catch (27%), followed by sharks (26%), rays (25%), mahimahi (*Coryphaena hippurus*) (12%), and tunas and billfish (10%). Non-target and discard species, such as rays and sea turtles, accounted for over half of the total catch. Catch per unit effort (CPUE; number of individuals per 1,000 hooks) was higher with control hooks compared to appendage hooks for all species' categories except rays; appendage hooks caught 52% fewer sea turtles and 23% fewer tunas and billfish than standard hooks, which represents a significant reduction in bycatch of endangered and other species. No differences were found in the AHL for sea turtles, suggesting use of the appendage may not incur additional advantages regarding turtles' post-release survivorship. Despite lower catch rates for marketable species, such as sharks and mahimahi, use of the appendage resulted in dramatic reductions in catch rates of sea turtles. The results suggest that large scale adoption of hooks with a significantly wider hook dimension could be an effective conservation measure to maintain marine biodiversity while allowing for continued fishing.

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Introduction

Fisheries bycatch has been implicated in the population declines of numerous species of marine megafauna, most notably elasmobranchs and sea turtles (Lewison et al. 2004; Dulvy et al. 2008; Wallace et al. 2010). Reducing the incidental and unwanted capture of sea turtles is a priority for industry, managers, and conservationists (Hall et al. 2000), and efforts are underway to improve the selectivity of fishing gear worldwide. Consumer demands for sustainable seafood also play an increasingly important role in the economics of fishing, with a growing awareness to reduce overfishing and promote clean fishing methods with minimal waste, or discards, and these attitudes have come to the forefront in making seafood choices (Roheim and Sutinen 2006). Fisheries management regimes that incorporate and regulate such technologies and strategies can be the drivers to effective mitigation and greatly improve fishing selectivity on a global basis.

Pelagic longline operations, which are known to inadvertently hook and entangle sea turtles, have specifically been implicated in increasing the risk of extinction for Pacific leatherback (*Dermochelys coriacea)* and loggerhead (*Caretta caretta)* sea turtle populations (Spotila et al. 2000; Kamezaki et al. 2003). However, recent research has demonstrated that modifications in traditional gear, such as type and size of hook and bait can significantly reduce these unwanted interactions and thus pose a reduced threat on globally declining sea turtle populations (see Gilman et al. 2006). In the U.S. Atlantic and Pacific swordfish (*Xiphias gladius)* fisheries (shallow-set, <100 m), the combination of relatively large 18/0 circle hooks and mackerel bait effectively reduced the capture rate of sea turtles by 60–90% when compared to traditional J-style 9/0 hooks (Watson et al. 2005; Gilman et al. 2007). As such, current U.S. law requires use of relatively large circle hooks in all swordfish-setting longline operations in both the Pacific and Atlantic Oceans (Gilman et al. 2006), and efforts are underway to encourage similar adoptions in global Regional Fisheries Management Organizations.

The Food and Agriculture Organization (FAO) of the United Nations defines fishing selectivity as a "fishing method's ability to target and capture organisms by size and species during the fishing operation allowing non-targets to be avoided or released unharmed" (FAO 2005). Recent field trials indicate that circle hooks act both to reduce the frequency of capture of sea turtles and may also reduce the severity of injury imposed by the hooking event (Watson et al. 2005; Gilman et al. 2007; Read 2007; Piovano et al. 2010; Sales et al. 2010). On a circle hook, the point is perpendicular to the shank such that the point curves inward and is less exposed, whereas J- or tuna-style hooks have the point of the hook parallel to the shank (Fig. 1) (Cooke and Suski 2005; Serafy et al. 2009). The rounded feature of the circle hook increases the minimum total width, which is assumed to play a role in the reduced frequency of capture when using wider hooks (Piovano et al. 2010). Results from numerous longline fishing experiments support the adoption of circle hooks that have a gape (or "gap") width, which is the shortest distance between the point and shank, and a straight minimum width relatively larger than the traditional hooks in order to effectively reduce turtle bycatch (Watson et al. 2005; Read 2007).

There is limited information on the effects of hook extensions, or "appendages", on terminal fishing gear in fishes (Willis and Millar 2001; Barnes et al. 2004), and none in sea turtles. The addition of a wire appendage, which projects posterior from the hook eye at an angle of

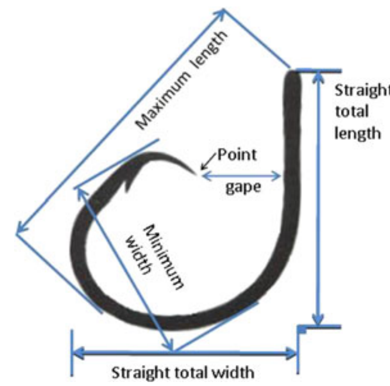

Fig. 1 Dimensional terms of a circle hook (adapted by Yokota and Boggs, pers. comm.)

approximately 45° to the shank (Fig. 2), is thought to form a physical barrier to ingestion by extending the hook's width dimension. In addition to reducing catch rates of undersize fish, the width extension is also believed to reduce incidental mortality by interfering with a fish's ability to swallow the hook and have it lodged in the gut compared to a more shallow or superficial hooking (Willis and Millar 2001). This would be most valuable for improving probability of survival for discarded catch, such as undersize or non-marketable fish or protected species, where mortality rates for fish caught and released were

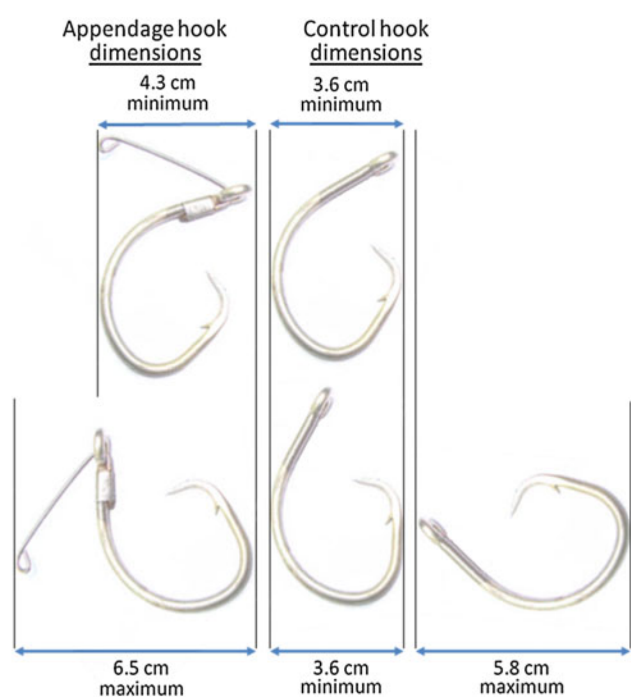

Fig. 2 14/0 circle hook with appendage and standard control 14/0 circle hook

found to range from 0 to 89% across many freshwater and marine species (Muoneke and Childress 1994).

Appendage hooks were tested in a longline fishery targeting snapper (*Pagrus auratus*) in New Zealand, whereby hooks were modified by the addition of 20-mm and 40-mm wire appendages (Willis and Millar 2001). Modified hooks had lower reduced overall catch rates, yet selected for larger, more marketable fish, and thus, the economic loss was negligible. Additionally, the use of the appendage resulted in a markedly lower rate of gut-hooked fish when compared to controls, with an assumed increase in probability of survival for those fish that were discarded. The results suggest that use of such modified gear in a commercial fishery could result in maintained high rates of export-quality fish, while simultaneously reducing capture and mortality of discards (Willis and Millar 2001), all of which contribute to long-term sustainability in fishing.

The issue of anatomical hook location (AHL) in sea turtles with regards to probability of survival is as yet unresolved, largely due to the inability to observe a large enough sample size of animals post-hooking either in captivity or via telemetry in the wild. Even among recreational fish, with catch rates orders of magnitude higher than those of sea turtles caught in most pelagic fisheries, there were only five species of fish for which active researchers believed there was a reasonable understanding of catch-and-release angling effects (Cooke and Suski 2005). To summarize, it has been proposed that (1) deep hooking leads to bleeding that in turn leads to mortality, (2) hooking in the gills increases hook removal times, and (3) delayed hook removal leads to increased mortality (Cooke and Suski 2005). With regards to sea turtles, at present, there is no quantitative evidence suggesting differential survivorship post-release from fishing gear based on differences in the AHL. However, debate is ongoing whether a deeply ingested hook incurs less damage due to the hook's ability to be excreted from the body with minimal damage, or if the damage due to hook removal from a turtle's mouth may incur higher chance of infection and subsequent mortality. This study is not intended to resolve this issue but rather to assess potential differences in AHL that may be helpful in understanding impacts of different types of longline interactions once more information is gathered on the subject of post-release mortality in relation to AHL.

Costa Rica's shallow-set pelagic longline fishery operating out of Playa del Coco routinely uses a combination of circle hooks (14/0 and 15/0 with both 0° and 10° offset, without an appendage) and baits (e.g., squid, sardines, skipjack tunas, tuna stomachs, and thresher sharks [*Alopias* spp.]). The primary target species, dorado, or mahimahi (*Coryphaena hippurus*) are caught primarily from November to March for both domestic consumption and export to the United States. Mahimahi is a highly migratory seasonal resource and is most abundant in the region during the last quarter of the year (Campos et al. 1993; Kraul 1999). When mahimahi is not present, the year-round Costa Rican longline fishery often shifts their target to sharks, described as a "complementary catch" that is retained and sold. While not specifically targeting billfishes, the fishery also retains billfishes of marketable size or they are utilized as bait.

Despite the use of "turtle friendly" gear, the fishery has relatively high catch rates of sea turtle and other bycatch species (Arauz et al. 2004; Swimmer et al. 2006). Thus, this fishery offers unique conditions for testing the effectiveness of specific strategies to improve fishing selectivity in a pelagic longline operation, as there is a high potential for sufficient sample sizes for robust statistical inference of both target and bycatch species. The primary objectives of this study were to investigate the effects of a circle hook modified with a wire appendage with respect to (1) catch rates of target species such as tunas, mahimahi, and sharks, (2) non-target and discarded species such as sea turtles and rays, and (3) location of hooking in sea turtles. These field trials were conducted in order to evaluate the use of an appendage hook as an effective conservation tool in an artisanal longline fishery in Costa Rica.

Materials and methods

Fishing operations

Experiments to test catch rates of target fish species and sea turtles were conducted on the commercial longline fishing vessel F/V Don Christopher operating from Playas del Coco in the Gulf of Papagayo, Costa Rica. Five trips targeting mahimahi, tunas, billfishes, and sharks were conducted in the Costa Rican Exclusive Economic Zone (EEZ) from February 2007 to June 2007. In total, 54 longline sets were observed, all of which were located between coordinates 5°–10°N, 90–84°W.

A size 14/0 Mustad circle hook with 0° offset was used as the standard or control hook, and the appendage hook was identical, except that it had a wire appendage attachment (Fig. 2). With the appendage, the maximum dimension of the appendage hook was increased by 10% and the minimum dimension of the hook by 19%. The minimum and maximum dimensions measure 4.3 and 6.6 cm for appendage and 3.6 and 5.8 cm for control hooks. Hooks of each type were alternated along the length of the monofilament mainline, with four hooks deployed between successive longline floats. Figure 3 depicts a basic longline configuration, whereby the mainline is suspended by a series of floats. The actual depth of the hooks is determined

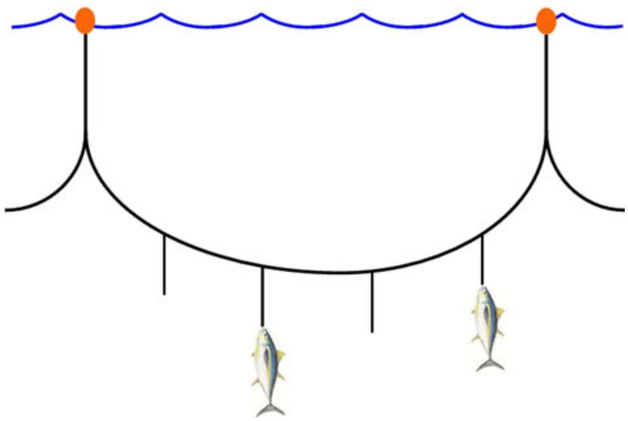

Fig. 3 Depiction of a pelagic longline, whereby mainline is suspended by a series of floats, with baited hooks at terminal ends of the gangions

in large part by the length of the mainline deployed between floats, the length of the floatlines and branchlines (gangions), as well as oceanographic conditions.

To reduce the variance in catch rates, only one bait type was used (Humboldt squid, *Dosidicus gigas*) cut into sections. Monofilament gangions (7 m) were attached along the length of the monofilament mainline. Lines were deployed in the morning and soaked for approximately 12 h before retrieval in the late afternoon or evening. For each longline set, standard information such as times and locations of initial set and retrieval, species caught per hook type, and hook position between floats was recorded.

Total catch and hook type

The total catch of each species was enumerated, and the catch data were later grouped into the following six categories: (1) mahimahi, (2) sea turtles (*Lepidochelys olivacea* and *Chelonia mydas*), (3) rays (pelagic stingrays, *Pteroplatytrygon violacea* and manta rays (Mobulidae), (4) sharks (Carcharhinidae, Sphyrnidae, Alopiidae, and Pseudocarchariidae), (5) tunas and billfishes (Scombridae, Xiphidae, and Istiophoridae), and (6) other finfish.

Catch rates were expressed as catch per unit of effort (CPUE) and calculated as the number of animals captured per 1,000 hooks for all analyses. For the six species categories, it was assumed that each animal caught was a randomly selected individual from the same population. CPUE data were $\log(x + 1)$ transformed to account for unequal variances and when at least one animal per species group was caught by one hook type in a set, but not the other. A paired *t*-test was used to test the null hypotheses that there was no difference in mean catch rate (over sets) between the two hook types for each species group, except for 'other finfish' since so few were caught. Statistical analyses were conducted using the R program (R Development Core Team 2009) at the 5% level of confidence.

The hook position between floats, labeled 1, 2, 3, or 4, was recorded for individual animals during haulback. Statistical summaries indicated differences in catch rates between hook positions and fishing months; therefore, a generalized linear model (GLM) was used to explore the effects of hook type and position and fishing month on catch rates for four frequently caught species: the olive ridley turtle, mahimahi, pelagic stingray, and silky shark. Separate models were fit to individual species, and the dataset was constructed for a species catch of "1" if the hook type or position caught an individual or "0" if no individuals were caught. Data were deleted if the hook type or position was unknown. For each species, the GLM predicts mean catch (μ_i) as number of individuals using three categorical with a log link: $\log(\mu_i) = N_i + H_i + T_i + P_i + \log(E_i)$ where N is the mean local abundance; H, hook type effect; T, time (month); P, hook position effect and offset E is the number of hooks deployed during longline operation i. GLMs were fitted using R [R Development Core Team 2008, version 2.7.2 for Linux] and considered a negative binomial response distribution. Stepwise model selection was conducted by AIC. GLMs indicated that hook positions could be statistically grouped as shallow (hooks 1 and 4) and deep (hooks 2 and 3), thus establishing four possible combinations for each longline set, consisting of two hook types and two hook positions. No GLMs were conducted on species categories as vulnerability to capture by hook depth and relative abundance in the fishing area apparently differs by species.

Sea turtle morphometrics and hooking location

Detailed information including sex and morphometric measurements was collected for sea turtles caught during these trials. However, this was not possible for all turtles captured, especially those that were too large to land safely. Curved carapace length (CCL) was measured from the nuchal scute to the posterior tip of the dorsal surface. Curved carapace width (CCW) was measured at the widest point of the carapace, and straight carapace height (SCH) was measured at the widest point between the plastron and the highest point of the carapace.

As shown in Fig. 4, the anatomical position of hook lodging on sea turtles was recorded using the following classifications: entangled in float lines, gangions, or main line; flipper, either fore or hind; mandible, or jawbone; maxilla, including roof of the mouth or maxillary bone; hook swallowed; or not determined (e.g., hook became

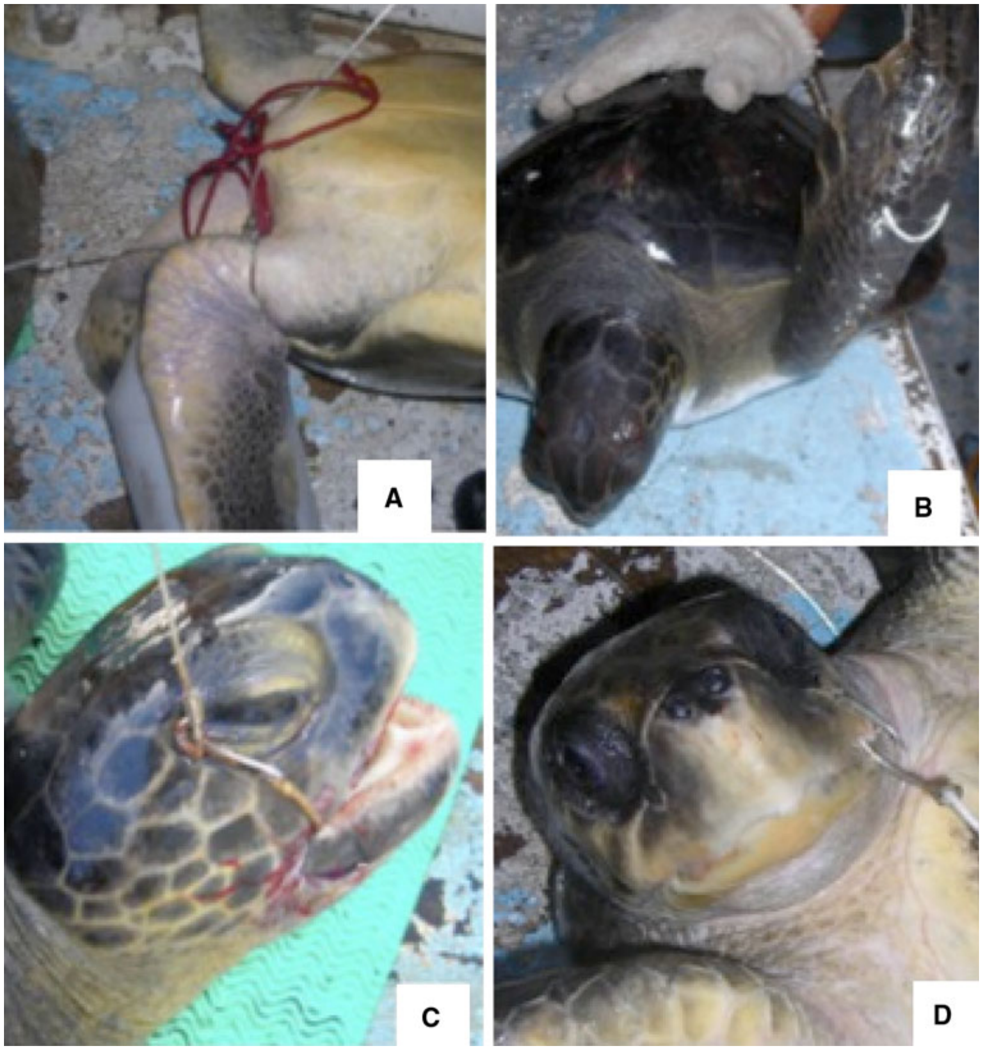

Fig. 4 Classification used to describe the anatomical hooking position in sea turtles captured during longline fishery operations in the Costa Rican EEZ during 2007. **a** Entangled in line, **b** Flipper hooking, **c** Maxilla or mouth hooking, **d** Mandible

dislodged before decking the turtle). For analytical purposes, the categories were further grouped as either: external or light hooking, mandible or "mouth" hooking, or swallowed. A chi-square test of independence was used to test the null hypothesis that the anatomical location, a turtle was hooked, was independent of hook type. Hook locations were not determined for fish.

To test the null hypothesis that hook type, turtle size, and AHL were mutually independent, we used a G^2 statistic (distributed approximately as a chi square) 3-way contingency table, based on a log-linear method (Dulvy et al. 2008) with categorical variables hook type, hook location, and turtle size (CCL <52 cm, CCL >52 cm). In these tests, there is an inherent bias given that a relatively large number of turtles too large to bring on board were not measured and therefore omitted from the analysis.

Results

Total catch and hook type

A total of 43,424 hooks were deployed on 54 sets during five fishing trips. Roughly half ($n = 22{,}031$; 50.7%) of the hooks were control (14/0 circle) hooks, and the remaining ($n = 21{,}393$; 49.3%) were appendage hooks. The average number of hooks per set was 804 ± 94 (range 420–982). A total of 1,811 marine animals were captured, and hook type was determined for 1,763 animals. The number of individuals and CPUE by taxonomic group and hook type are shown in Table 1. Species with fewer than four individuals caught were not listed. The overall catch rate on control circle hooks (CPUE = 47.8) was 30% greater than on appendage hooks (CPUE = 33.2). The average, median, standard deviation, minimum, and maximum catch

Table 1 Total catch in number and total catch per unit effort (CPUE) per 1,000 hooks for 54 sets using standard (control) 14/0 circle hooks and appendage 14/0 circle hooks

Common name	Species name	Total		Standard		Appendage		No data
		Catch	CPUE	Catch	CPUE	Catch	CPUE	
Target species								
Dolphinfish/Mahimahi	*Coryphaena* spp.	211	4.86	122	5.54	88	4.11	1
Sea turtles		488	11.23	321	14.57	151	7.05	16
Olive ridley	*Lepidochelys olivacea*	468	10.78	309	14.03	143	6.68	16
Green turtle	*Chelonia mydas*	20	0.46	12	0.54	8	0.37	0
Rays		455	10.48	221	10.03	215	10.05	19
Pelagic stingray	*Pteroplatytrygon violacea*	408	9.40	199	9.03	194	9.07	15
Manta ray	*Mobula* spp.	47	1.08	22	1.00	21	0.98	4
Sharks		460	10.59	270	12.25	184	8.6	6
Silky shark	*Carcharhinus falciformis*	413	9.51	243	11.03	166	7.76	4
Thresher shark	*Alopias* spp.	24	0.55	13	0.59	10	0.47	1
Smooth hammerhead shark	*Sphyrna zygaena*	13	0.30	8	0.36	5	0.23	0
Crocodile shark	*Pseudocarcharias kamoharai*	6	0.14	4	0.18	1	0.05	1
Ocean white tip shark	*Carcharhinus longimanus*	4	0.09	2	0.09	2	0.09	0
Tunas and billfishes		175	4.03	106	4.81	66	3.08	3
Pacific sailfish	*Istiophorus platypterus*	68	1.57	46	2.09	21	0.98	1
Striped marlin	*Kajikia audax*	34	0.78	19	0.86	15	0.70	0
Yellowfin tuna	*Thunnus albacares*	32	0.74	18	0.82	13	0.61	1
Blue marlin	*Makaira nigricans*	22	0.51	12	0.54	10	0.47	0
Wahoo	*Acanthocybium solandri*	11	0.25	5	0.23	5	0.23	1
Swordfish	*Xiphias gladius*	8	0.18	6	0.27	2	0.09	0
Others		4	0.09	1	0.09	3	0.14	3
Ocean sunfish	*Mola mola*	4	0.09	1	0.05	3	0.14	3
Total (includes species not listed)		1793 (1811)		1040 (1052)		707 (711)		48

No data indicated when hook type not identified

Table 2 The average, median, standard deviation, minimum, and maximum CPUE by hook type and species category by hook type and set

Category	% Catch	Standard hooks ($n = 22{,}031$)					Appendage hooks ($n = 21{,}393$)					p value (t test)
		Avg	Median	SD	Min	Max	Avg	Median	SD	Min	Max	
Mahimahi	11.7	11.15	4.76	10.69	2.19	37.88	7.83	3.59	8.60	2.33	38.89	0.3855
Sea turtles	26.9	14.67	13.79	9.58	2.21	45.24	8.56	6.99	4.66	2.33	19.05	<0.0001
Rays	25.1	14.63	7.32	12.60	2.33	48.47	12.75	7.74	10.75	2.05	37.21	0.6041
Sharks	25.7	14.49	9.52	12.22	2.22	54.79	10.30	5.55	10.05	2.22	51.63	0.0550
Tunas and billfishes	10.2	6.38	4.70	4.01	2.21	17.78	4.90	2.38	3.21	2.03	13.33	0.0014

rates are shown in Table 2, along with results of t-tests. Sea turtles as a group represented the greatest total catch in number (27%), followed by sharks (26%), rays (25%), mahimahi (12%), tunas and billfish (10%), and others (0.4%) (Fig. 5).

Capture rates

Sea turtles ($n = 488$) were caught in all 54 sets. On average, appendage hooks caught 52% fewer sea turtles than control hooks, which was statistically significant ($df = 53$, $t = 5$, $p < 0.0001$). Of the 488 sea turtles captured, the majority were olive ridley turtles ($n = 468$; 95.9%), followed by green turtles ($n = 20$; 4.1%). All green turtles and 96% of olive ridley turtles were released alive.

Mahimahi catch rates declined over the course of experimental trips and were caught in 34 sets (63% of total), with a peak in abundance in March. Capture rates of mahimahi on appendage hooks were lower than capture rates using control hooks, but were not statistically

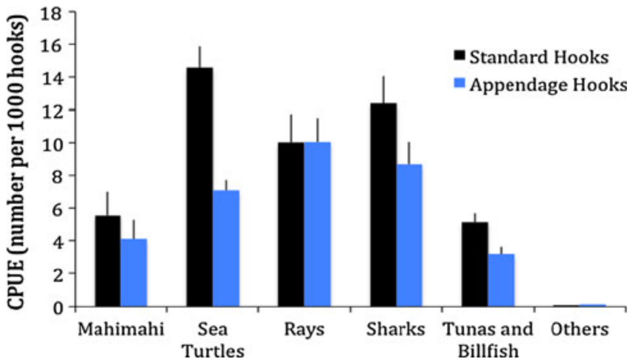

Fig. 5 Catch rate (mean, SE) by hook type for major categories of species during 54 longline fishing sets within the Costa Rican Exclusive Economic Zone

significant overall ($df = 33$, $t = 0.88$, $p = 0.3855$). Tunas and billfishes were caught in 49 of the 54 sets, and the majority of the catch was composed of Pacific sailfish, striped and blue marlin, and yellowfin tuna (Table 1). In 34 sets, the catch rates of tunas and billfishes were greater on control hooks than appendage hooks, and during 16 sets, none were caught on appendage hooks. On average, the catch rate on appendage hooks was 23% less than on control hooks, which was statistically significant ($df = 48$, $t = 3.37$, $p = 0.0014$).

Sharks were caught in 51 of 54 sets, with the predominant species being silky sharks (90%). The catch rate per set for sharks as a group was greater on control hooks in 29 of the 51 sets, which showed marginal significant difference ($df = 50$, $t = 1.96$, $p = 0.0550$). Rays were caught in 44 of 54 sets and were mostly comprised of pelagic stingrays (90%). The overall catch rate for rays was nearly equal between hook types ($df = 43$, $t = -0.52$, $p = 0.6041$).

Hook type, position, and temporal variability

The GLMs incorporating hook type, position, and month had similar significance as the t-tests with regard to hook type (Table 3). Appendage hooks caught 52% fewer olive ridleys ($p < 0.001$) and 31% fewer silky sharks ($p < 0.05$). There were large and statistically consistent effects ($p < 0.001$) of hook position as the deeper hooks caught more olive ridleys (2.3×), dolphinfish (2.0×), pelagic stingrays (1.5×), and silky sharks (1.8×). Dolphinfish catch rates were highest in March (7.9×) and April (4.3×) and declined dramatically during May and June. Silky shark catch rates exhibited a decline from February to June. There were no significant differences in monthly catch rates for olive ridley turtles and only marginal effects for sting ray.

Sea turtle morphometrics and hooking location

Of the 468 olive ridleys captured during this study, measurements were taken for 341 individuals. The primary reason for not measuring turtle size was due to animal being too large to bring on board safely. Of the turtles measured, 71% were of adult size (>52 cm), with a ratio of females to males being approximately 2.5:1. The average carapace dimensions (CCL, CCW, and SCH) for female and male olive ridley and green turtles are summarized in Table 4. Between hook types, there were no differences found in the AHL: external (light), mandible, or swallowed ($\chi^2_{0.05} = 3.7596$, $df = 2$, $p = 0.1526$). As shown in Fig. 6, the majority of hookings were in the mandible, or "mouth" category, with 78% using control hooks and 72% using appendage hooks. Regarding the role of turtle size (CCL), AHL, and hook type, there was no evidence of a relationship between the three variables ($G^2 = 11.9$, $df = 7$, $p = 0.1039$). This analysis did not include turtles whose sizes were not determined.

Discussion

As observed in these experimental field trials, non-target species comprised greater than half the total catch when compared to marketable catch, confirming the need to identify tools to improve fishing selectivity. This study demonstrates that the addition of an appendage increasing hooks' maximum and minimum dimensions by 11 and 19%, respectively, had significant effects on catch rates of sea turtles and tunas and billfishes in the size classes found in waters of the eastern tropical Pacific (ETP). These findings are useful to conservation biologists, fisheries managers, and fishermen with a strong, shared motivation to improve the selectivity of longline fishing gear both locally and globally.

Strategies to reduce sea turtle interactions must meet strict criteria if they are to be adopted. Specifically, they must be effective at reducing bycatch and commercially viable in maintaining target species catch rates. In addition, while a number of factors influence effective implementation of bycatch reduction technologies, the impacts of modifications to fishing gear are often directly linked to the fishermen's ability or incentives to implement the proposed changes (Campbell and Cornwall 2008). In this study, the use of an appendage on a commonly used circle hook reduced the total catch of marine animals by approximately 30%, though results varied by species. Although the overall lower catch rates for target species, particularly for sharks and mahimahi, may suggest that this modification would not meet the criteria necessary for adoption as a viable

Table 3 Estimates (95% confidence intervals) for each parameter estimated by generalized linear models for four species

Coefficient	Olive ridley ($n = 434$)	Mahimahi ($n = 175$)	Pelagic stingray ($n = 374$)	Silky shark ($n = 413$)
(intercept)	0.00744***	0.00086***	0.00747***	0.01924***
Hook type (appendage)	0.473 (0.23–0.71)***	0.711 (0.32–1.10)°	1.006 (0.76–1.25)	0.684 (0.38–0.99)*
Hook depth (hooks 2 and 3)	2.308 (2.07–2.55)***	1.966 (1.57–2.36)***	1.523 (1.28–1.77)***	1.749 (1.44–2.06)***
Month (March)	1.242 (0.73–1.75)	7.865 (6.65–9.08)***	0.343 (0–0.89)***	0.468 (0–0.86)**
Month (April)	0.607 (0.04–1.18)	4.261 (3.01–5.51)*	1.891 (1.40–2.38)*	0.256 (0–0.86)***
Month (May)	1.215 (0.68–1.75)	0.754 (0–2.17)	1.389 (0.89–1.89)	0.345 (0–0.93)***
Month (June)	1.234 (0.71–1.76)	0.721 (0–2.11)	0.425 (0–0.98)**	0.144 (0–0.78)***
Deviance explained (%)	20.8	29.0	25.3	15.8

Statistical significance *** $0 \leq p < 0.001$, ** $0.001 \leq p < 0.01$, * $0.01 \leq p < 0.05$, ° $0.05 \leq p < 0.1$

Table 4 Average carapace dimensions for female and male olive ridley and green turtles caught as bycatch during fishery observations in the Costa Rican EEZ

Species	Combined	Females			Males		
	CCL (cm)	CCL (cm)	CCW (cm)	SCH (cm)	CCL (cm)	CCW (cm)	SCH (cm)
Olive ridley	$n = 341$	$n = 174$	$n = 174$	$n = 173$	$n = 70$	$n = 70$	$n = 69$
Lepidochelys olivacea	56.3 ± 10.2	61.0 ± 5.2	66.8 ± 5.2	22.8 ± 2.2	64.1 ± 3.7	69.4 ± 4.2	23.0 ± 1.5
	Range: 30–79	Range: 53–79	Range: 56–78	Range: 17–35	Range: 54–73	Range: 57–79	Range: 20–26
Green turtle	$n = 19$	$n = 8$	$n = 8$	$n = 8$	–	–	–
Chelonia mydas	51.0 ± 12.5	63.6 ± 5.7	63.1 ± 6.1	23.6 ± 2.8			
	Range: 32–73	Range: 56–73	Range: 54–73	Range: 20–29			

CCL Curved carapace length, *CCW* curved carapace width, *SCH* straight carapace height

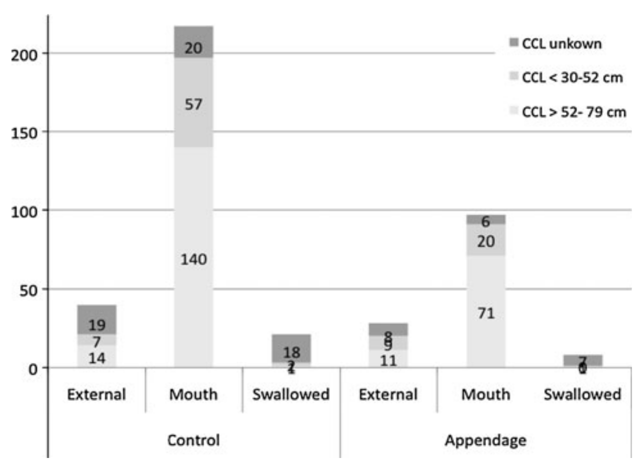

Fig. 6 Relative percentages of anatomical hook locations by hook type and turtle size (curved carapace length [*CCL*])

marine conservation tool, the dramatic difference in catch rates of sea turtles and lack of statistical significance for target species should encourage more studies evaluating the use of modified hooks.

This study confirmed the abundance and diversity of fauna vulnerable to capture in longline fishing gear in the Costa Rican EEZ. Sea turtles as a group constituted the primary catch in this study, with the vast majority (96%) being olive ridleys. The presence of two large synchronous olive ridley sea turtle nesting beaches off the coast of northwestern Costa Rica is likely responsible for the high relative abundance of sea turtles in the region during the time of the study (Cornelius 1982). Despite their vulnerability to capture in fishing gear, recent estimates suggest abundance of olive ridley turtles at approximately 1.39 million individuals in the coastal and oceanic waters of the ETP (Eguchi et al. 2007). Additionally, it is believed that that their numbers are still increasing, likely as a result of effective protection programs on nesting beaches aimed to increase hatchling recruitment that began in the 1990s (Eguchi et al. 2007). In this study, the rate of sea turtle capture was ca.14 and 9 individual turtles caught per 1,000 hooks set on standard and appendage hooks, respectively, which is comparable to previous reports of similar research in this area with seasonal differences (CPUE ~19 turtles/1,000 hooks; Swimmer et al. 2010). Despite the fact that nearly 100% of turtles were released alive, the frequency of capture and potential impact on relatively healthy populations of olive ridley turtles reinforce the need to identify tools to improve fishing selectivity.

Typically, the carapace length of adult olive ridleys ranges from 53 to 70 cm, with the majority of animals caught during this study fitting within that range (Zug et al. 2006). The 2.5:1 ratio of adult females to males suggests the abundance of reproductive females in these fertile fishing grounds. Results from this study in combination with previous observations indicate that adult olive ridley sea turtles are located predominately in inshore waters, whereas smaller, immature individuals likely favor pelagic waters (Arauz and Ballestero 2003). Therefore, capture rates of sub-adult turtles are disproportionately higher than adult turtles in these nearshore pelagic fisheries due to their shared habitat with mahimahi and other target species, such as sharks and rays.

One of the main target species, mahimahi, represented less than 15% of the catch, which, in comparison with other years (on standard hooks), was relatively low and even further reduced when using appendage hooks (Arauz et al. 2004). These low catch rates are likely due to the timing of this study, since experimental sets were deployed between February and June when mahimahi were not at peak abundance. Our analysis confirmed this finding with clear differences in catch rates between months. Because fishermen in the Costa Rican longline fishery tend to shift target to sharks when mahimahi is not as abundant, the capture of marketable sharks is also of economic importance.

Silky sharks, although relatively abundant throughout their range, are highly susceptible to longline fishing gear and subsequently comprise a large component of numerous longline fisheries catch (Cortés et al. 2010). Bonfil (1994) estimated that nearly a million silky sharks were caught in tuna longline fisheries in the southern and central Pacific in the early 1990s. Because silky sharks are not a preferred species for their meat, it is believed that most sharks are taken for their fins (Camhi et al. 2009). The CPUE of silky sharks was lower on appendage hooks when the effects of hook position and time (month) were removed. Reduced catch rates may prove valuable in future efforts to identify means to reduce capture of sharks in fisheries where they are discarded, perhaps by further elongation of the appendage or some other modification. Because certain species of sharks and sea turtles share traits such as longevity, slow growth, late maturation, and low natural mortality, they are particularly susceptible to fishing pressure, making ecosystem solutions to reduce the overall impact of fisheries on sensitive species an important goal. Despite our findings that most sharks in this study were released alive, their post-release survivorship is uncertain.

A relatively high capture rate of rays was noted during this study, particularly pelagic stingrays, which are highly vulnerable to pelagic longline gear worldwide (Camhi et al. 2009) and are often landed alive (Kerstetter and Graves 2006; Carruthers et al. 2009), despite extensive mouth and jaw injuries (Camhi et al. 2009). Rates of survival after their release are unknown, yet significantly improve with proper handling (e.g., not cutting off barbed stinger on their tail) and believed to be higher on animals caught on circle vs. J hooks (Kerstetter and Graves 2006; Carruthers et al. 2009). The appendage was not effective at reducing capture rates of stingrays. Piovano et al. (2010) investigated the role of hook and bait and found that use of relatively wide circle hooks reduced capture rates of stingrays in an Italian swordfish fishery when compared to traditional Spanish J-style hooks. It was further recommended that the European Union adopt use of wide circle hooks as a management strategy and conservation tool for stingrays in the Mediterranean Sea to prevent further population declines (Piovano et al. 2010). Further research is warranted in this area to determine factors influencing the incidental capture of stingrays in fisheries. Such efforts are likely to be assisted by fishermen with high motivation to identify effective strategies to reduce these captures both for personal safety given the rays' venomous spines as well as economic loss. Similar to previous longline experimental field trials (Kerstetter and Graves 2006; Carruthers et al. 2009), rays occupied nearly a quarter of all baited hooks, thereby reducing potential capture of high market value fish.

Primarily in freshwater fisheries, and to a lesser extent in marine fisheries, there has been extensive research in the area of best practices in catch-and-release aimed to enhance the survival of fishes after their return to the water (Muoneke and Childress 1994). The anatomical hook location (AHL) is considered to be one of the most important factors affecting the mortality of fish caught and released, with considerably higher rates of mortality associated with "deep hookings" (e.g., esophagus, gills, stomach; (Alos et al. 2009a, b). Factors associated with deep hooking include species-specificity, fish size, types of hook and bait, and line leader characteristics (Alos et al. 2009a, b). However, in an analysis of 12 species of recreational fish caught, the most important predictor of deep-hooking incidence was fish size, with larger fish significantly more likely to be deep-hooked than smaller fish (Alos et al. 2009b).In the case of sea turtles caught on pelagic longline fishing gear, hook type and bait have been shown to influence type of hooking, whereby J hooks (vs. circle hooks) and fish bait (vs squid) have shown a higher frequency of deep hooking (Watson et al. 2005; Sales et al. 2010). Despite a lack of hard evidence, it is largely assumed that, similar to fishes, a more shallow hooking leads to higher post-release survival (Swimmer et al. 2006). While factors such as turtle size, hook type, and longline bait have been discussed in relation to frequency of capture on longline gear, the role of turtle size in relation to the AHL has not been previously investigated. Inspired by the results from recreational fisheries, we included turtles' size in our investigation of factors affecting AHL.

We found that turtles were most commonly hooked in the mandible, which coincides with reports of circle hook performance in other experiments (Bolten and Bjorndal

2002, 2003; Watson et al. 2005). It is generally assumed that this type of hooking allows for the relatively easy removal of the hook with minimal damage to the animal (Swimmer et al. 2006). The use of the appendage hook had no effect on the AHL, so its use would not confer benefits related to differential rates of survivorship or mortality when compared to a standard circle hook design. Additionally, analysis of the effect of turtle size (CCL) also did not suggest an effect of AHL due to turtle size. Efforts are underway to provide empirical data, largely through the use of satellite telemetry, to build upon previous estimates of post-release mortality (Ryder et al. 2006). It has been increasingly clear that in shallow-set fisheries where turtles can reach the surface and breath while they are hooked or entangled in longline gear, there is nearly 100% immediate survivorship, as has been shown in this and previous studies (Gilman et al. 2006; Swimmer et al. 2010). We are engaged in additional research that aims to understand sub-lethal physiological and hematological effects of these interactions as well. We strongly believe that safe handling of turtles brought on board via dip net, including the removal of as much gear as possible, likely plays a critical role in determining an animal's post-release survival and well-being. As has been developed for fish in catch-and-release fisheries (Cooke and Suski 2005), we aim to develop and refine general guidelines for the successful release of sea turtles to enhance survivorship and to include considerations for factors such as species and life history stage.

The significant increase in catch rates for the two deep middle hooks compared to the shallower outside hooks is intriguing for surface longline gear. The actual depth difference among hooks is impossible to determine post hoc, as actual hook depth is a function of numerous operational and oceanographic variables (Bigelow et al. 2006). Given the variables at play, we hypothesize that the two middle hooks are approximately 5.5–7 m deeper than the shallower adjacent hooks. The findings suggest that the use of time depth recorders or other means to determine actual hook depth could improve our understanding of species' vulnerabilities by depth, and hence work to improve the selectivity and efficiency of longline fishing gear from this angle as well.

The observed high frequency of capture of non-target species emphasizes the need to identify means to improve fishing selectivity in pelagic longline fishing gear in the ETP as well as in other biologically rich marine environments. Based on the sea turtle conservation value alone, it can be concluded that the use of appendage hooks would be a viable option for reducing sea turtle interactions during fishing operations conducted in the shallow set mahimahi longline fishery of Costa Rica. However, because of the associated reductions in target species capture rates, it is unlikely that in the present form, the appendage hooks would be acceptable to the industry. We aim to further refine our findings to identify a modification that better serves both industry and conservationists. These modifications may include further testing of different hook and bait combinations, depth of fishing gear, time and location of fishing effort, and more rigorous studies using these cost effective methods to simultaneously reduce sea turtle and sensitive bycatch species in fisheries. Additionally, we will actively engage in both education and research within fishing communities to promote safe handling of non-target species in order to increase turtles' chances of survival once they are returned to sea.

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