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Circle hooks: Developing better fishing practices in the artisanal longline fisheries of the Eastern Pacific Ocean

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ABSTRACT

Since 2004, governments and non-governmental organizations, together with the fishing communities from nine countries, from Mexico to Peru, have implemented joint efforts to reduce incidental mortality of sea turtles in artisanal longline fisheries of the Eastern Pacific Ocean (EPO). These countries are involved in a Regional Sea Turtle Bycatch Program to achieve this goal. Circle hooks have been proposed as a way to mitigate incidental mortality of sea turtles. Thus, we analyze the performance of circle hooks in relation to J-style and tuna hooks on the hooking rates of target and non-target species in the artisanal surface longline fisheries of three of the participating countries with the largest sample sizes (Ecuador, Panama and Costa Rica). These fisheries target mahi-mahi, *Coryphaena hippurus*, or a combination of tunas, billfishes and sharks (TBS), and use different techniques and gear configurations to catch their targets. For the TBS fishery we presented the results of comparisons between tuna hooks and 16/0 circle hooks from Ecuador, Panama and Costa Rica, and between tuna hooks and 18/0 circle hooks in Costa Rica. For the mahi-mahi fishery, we analyzed the performance of 14/0 and 15/0 circle hooks in Ecuadorian vessels and 16/0 circle hooks in Costa Rican vessels vs. the traditional J-style hooks. A total of 730,362 hooks were observed in 3126 sets. Hooking rates for target and non-target species were not consistent for all fisheries and countries analyzed. However, circle hooks reduced sea turtle hooking rates in most of the comparisons.

1. Introduction

One of the key issues affecting marine conservation and fisheries management on a global scale is incidental mortality of non-target species (bycatch) during fishing operations. There is widespread interest in understanding and assessing the impacts of fishing on marine ecosystems, but in many cases, lack of information makes such assessment fraught with uncertainty. Several studies were focused on industrial longline fisheries around the world (Kerstetter and Graves, 2006; Sales et al., 2010; Ward

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et al., 2009; Yokota et al., 2006), but recent studies highlight the need to quantify the impacts of small-scale and artisanal fisheries on the different components of the megafauna that inhabit or migrate through the areas where those fisheries operate (Bugoni et al., 2008; Gillett, 2011; Lewison et al., 2004; Peckham et al., 2007). In the Eastern Pacific Ocean (EPO) the main incidental interactions of the longline fisheries targeting large pelagic fishes involve sea turtles (Largacha et al., 2005; Swimmer et al., 2010), although coastal gillnets also affect these populations (Peckham et al., 2007).

1.1. Artisanal longline fisheries of the region

Artisanal fisheries, which include a large number of small vessels (generally less than 10 m long), can collectively have a great impact on local turtle populations, and this issue is now gaining international attention (FAO, 2009). In the EPO, the artisanal longline fishery plays a significant role in local communities and economies (FAO, 2009; Peralta, 2009; Salas et al., 2011). There are surface and bottom longlines in this region. Surface longline fisheries can be classified in two large categories because of differences in hooks used and rigging; those targeting tunas (mainly yellowfin tuna, *Thunnus albacares*), billfishes (swordfish, *Xiphias gladius*, and marlins, *Makaira* spp., *Istiompax* spp., *Tetrapturus* spp. and *Kajikia* spp.) and sharks (dominated by Carcharhinidae) that will be abbreviated as TBS fisheries; and those targeting mahi-mahi, also called common dolphinfish, *Coryphaena hippurus* and referred to as mahi-mahi fisheries. A variety of fish species caught in both fisheries are listed in Appendix A. South American countries (i.e. Peru and Ecuador) show a marked fishing season for mahi-mahi in the austral summer and fish for TBS the rest of the year. Seasonal differences are less clear in other countries (from Costa Rica to Mexico) and there are vessels that pursue the same targets all year round depending on the availability of the resources in their fishing grounds. Panamanian TBS fishery targeting tuna shows a more consistent fishing season from April to August.

1.2. Sea turtles of the Eastern Pacific

Five species of sea turtles; olive ridley, *Lepidochelys olivacea*, black/green, *Chelonia mydas*, hawksbill, *Eretmochelys imbricata*, loggerhead, *Caretta caretta*, and leatherback, *Dermochelys coriacea* are found in the EPO. The olive ridley is the most abundant and most commonly captured by the coastal longline fisheries followed by the black/green sea turtle (Largacha et al., 2005; Swimmer et al., 2010). The remaining three species are much less common and they are subject of conservation concerns. For example, the Pacific populations of leatherback sea turtle are severely depleted (Limpus and Limpus, 2003; Sarti Martinez et al., 1996; Spotila et al., 2000), and are listed as critically endangered by the International Union for Conservation of Nature (IUCN, 2012). At their main nesting beaches in Mexico and Costa Rica, the reduction in the number of nesting turtles has reached 90% and 95% of the levels in the 1980s (Santidrián Tomillo et al., 2007; Sarti Martinez et al., 2007). These declines have been caused by multiple factors: egg poaching, predation on females or hatchlings from domestic or wild predators, environmental degradation and habitat loss (Wallace and Saba, 2009). But the incidental mortality caused by fisheries is clearly an important factor, because of the overlap of fishing grounds with sea turtle habitats and migratory routes (Shillinger et al., 2008).

1.3. The Eastern Pacific Regional Sea Turtle Bycatch Program

The program began in Ecuador in 2004, and has since expanded to 8 other countries: Mexico, Guatemala, El Salvador, Nicaragua, Costa Rica, Panama, Colombia and Peru. This participatory program involves the voluntary testing of circle hooks to reduce the mortality of sea turtles (Gilman et al., 2006; Watson et al., 2005), and other activities such as training of fishers in on-board sea turtle handling techniques to improve the survival of the turtles released after hooking or entanglement. Given the social and economic conditions in which these fisheries operate, it is necessary to achieve the objective without diminishing the productivity of the fisheries, and the efficiency of their operations.

This program was funded, organized and implemented by international and national NGOs, regional fisheries management organizations, national fisheries agencies and fishers cooperatives from the countries involved. It is the first truly regional, large scale, and consistent experimental effort to test circle hooks in multiple fisheries in the world.

1.4. Goal

Circle hooks can affect sea turtle mortality in at least three ways: (A) reducing the hooking rates of sea turtles; (B) reducing the proportion of sea turtles that are encountered dead at haulback; or (C) reducing the proportion of deep-hookings which are assumed to increase post-release survival (Ryder et al., 2006). The information from (A and B) is quite easy to acquire, and comes from direct observations. The information needed to evaluate in (C) is more complicated to obtain (Parga, 2012), and will be the outcome of tagging experiments (Swimmer et al., 2006), laboratory studies, or other ways to measure the likelihood of survival after hooking in different locations of the sea turtle body (external or internal).

In this study we focus on (A) analyzing the performance of circle hooks in relation to J-style hooks on the hooking rates of target and non-target species in the artisanal surface longline fisheries from the countries in which the Program had a longer period of study (Ecuador, Panama and Costa Rica). Some data for the other participating countries are available in different reports (e.g. Hall et al., 2007, 2008; Largacha et al., 2005; Mug et al., 2008).

2. Material and methods

2.1. Sampled fleet

The longline's main lines used in the region are made of two different materials; a buoyant type, polypropylene (PP) or polyethylene (PE) cordages, and a non-buoyant type, polyamide (PA) monofilament. Almost all longline vessels from Ecuador used the first type, while the latter is principally used by the longline fleets from Panama and Costa Rica. There are distinctive differences in gear geometry between the two types of longlines. A feature of surface longlines made of PP or PE cordages is that the mainline extends at or just below the surface of the sea because of its positive buoyancy. Therefore, all hooks are set at approximately the same depth. In contrast, PA monofilament, because of its negative buoyancy has a tendency to sink and forms a more pronounced catenary curve. Table 1 shows the principal configuration of longline gears used in the countries analyzed.

A variety of fishing hooks are used in longline fisheries of the region (Mituhasi and Hall, 2011). Fishers from Ecuador, Panama and Costa Rica use tuna hooks for TBS longlines although nominal hook sizes differ among countries (Table 1). For mahi-mahi, J-style hooks are used in Ecuador and Costa Rica. The sizes of these hooks in Ecuador (Nos. 4 and 5) are smaller than those used in Costa Rica (No. 2). In the case of Panama, no comparisons were analyzed in the present study because mahi-mahi fishers use only circle hooks (mainly 14/0) since at least 25 years ago.

There are also regional characteristics in longline baits. Jumbo flying squid, *Dosidicus gigas* is the main bait species for both TBS

Table 1
Characteristics of fishing gears used on artisanal longline vessels from Ecuador, Panama and Costa Rica. PP: polypropylene cordage, PE: polyethylene cordage, PAmono: polyamide monofilament.

Type	Tunas–billfishes–sharks			Mahi mahi	
Country	Ecuador	Panama	Costa Rica	Ecuador	Costa Rica
Mainline					
Material	PP	PAmono	PAmono	PP	PAmono
Diameter (mm)	3.5	3.0–3.5	2.0–4.0	2.5–3.0	2.0–4.0
Hook spacing (m)	50–65	27–36	20–50	27–32	18–36
Branch line					
Material	PP + PAmono	PAmono	PAmono	PP/PE + PAmono	PAmono
Diameter (mm)	3.5 (PP) 2.4–2.6 (PAmono)	2.0–3.0	1.8–2.0	2.0–2.5 (PP/PE) 1.2–1.8 (PAmono)	1.8–2.0
Length (m)	7.2–14.4 (PP) 10.8–14.4 (PAmono)	12.6–25.2	7.2–14.4	3.6–5.4 (PP/PE) 4.5–5.4 (PAmono)	7.2–10.8
Wire leader					
Diameter (mm)	–	1.5	1.4–1.8	–	1.4–1.8
Length (m)	–	0.25–0.5	0.3–0.7	–	0.3–0.4
Float line					
Material	PP	PAmono	PE or PP	PP	PE or PP
Length (m)	0.3–0.9	10–20	1–7	0.3–0.6	0.5–5.4
Hook[a]					
Conventional (control)	Tuna, size: Nos. 38, 40 with offset	Tuna, size: No. 8/0 with offset	Tuna, size: Nos. 34, 36 with offset	J-style, size: Nos. 4, 5 with offset	J-style, size: No. 2 with offset
Tested (experimental)	Circle, size: 16/0 with offset	Circle, size: 16/0 with offset	Circle, size: 16/0, 18/0 with offset and straight	Circle, size: 15/0, 14/0 straight	Circle, size: 16/0 with offset
Hooks between floats	2–3	3–12	3–5	5–6	3–6
Hooks per set	150–350	200–1500	150–1500	150–800	100–1500
Principal bait species	Jumbo flying squid, frigate tuna, round scad Live bait: Jumbo flying squid	Pacific pilchard, jumbo flying squid Live bait: Green jack, scads	Sardines, jumbo flying squid, tunas, elasmoblanch	Jumbo flying squid, frigate tuna, round scad	Jumbo flying squid, sardines

[a] Hook size refers to local names used by fishermen in each country.

Table 2
Characteristics of artisanal longline vessels from Ecuador, Panama and Costa Rica. TBS: tunas, billfishes and sharks.

	Ecuador		Panama	Costa Rica
	Mother ship	*Fibra*		
Length overall (m)	16–25	6–8	10–27	7–18
Hull type	Wood	Fiberglass	Steel, wood, fiberglass	Steel, wood, fiberglass
Engine	Diesel, inboard	Gasoline, outboard	Diesel, inboard	Diesel, inboard
Line retrieval	By hand	By hand	Hydraulic reel	Hydraulic reel
Number of crew	4–8	2–3	5–8	3–6
Number of days at sea	3–15 (mahi mahi) 3–25 (TBS)	7–24	3–35 (mahi mahi) 5–58 (TBS)	

and mahi-mahi in Ecuador, followed by round scad, *Decapterus* spp. and frigate tuna, *Auxis thazard thazard*. Costa Rican fishers prefer mainly jumbo flying squid for the mahi-mahi fishery and sardines, *Opisthonema* spp. for the TBS fishery. Panamanian fishers use mainly the Pacific pilchard, *Sardinops sagax*, small-size jumbo flying squid, green jacks, *Caranx caballus* and round scads (Table 1).

Longline vessels of the three countries differ in size and hull type (Table 2). Vessels from Panama and Costa Rica that operate PA monofilament longlines are equipped with hydraulic reels to haul up and store the mainline. Almost all Ecuadorian vessels operate their lines manually. In Ecuador, the vessels can operate individually or in mothership operations, where a larger vessel (around 20 m in length) tows usually 5–6 smaller boats called "fibras" (around 7 m long) to the fishing grounds, and provides storage for the catches and accommodation for the crews. Surface longlines are usually deployed before dawn, and recovered in the early afternoon. There are also some night sets, but they are relatively few.

2.2. Comparative fishing trials

In the period 2004–2010, a series of comparative fishing trials with J-hooks (both J-style and tuna hooks) and circle hooks were conducted onboard longline vessels in the Eastern Pacific Ocean. These trials were performed under standard fishing conditions on commercial fishing trips with the voluntary support and cooperation of local longline fishers. For the whole region, the Program sampled a total of 10,386 sets and almost 4 million hooks in 2295 fishing trips. These trips were made by 578 longline vessels from 38 different ports in the nine countries involved in the Program (Fig. 1). Although different sizes of circle hooks were tested (12/0–18/0), the analyses presented in this study were limited to the comparisons between J-style/tuna hooks vs. circle hooks for the countries with the greatest amount of effort (in number of hooks). Thus, the analysis were restricted to fisheries from Ecuador, Panama and Costa Rica summarizing a total fishing effort of 730,362 hooks in 3126 sets.

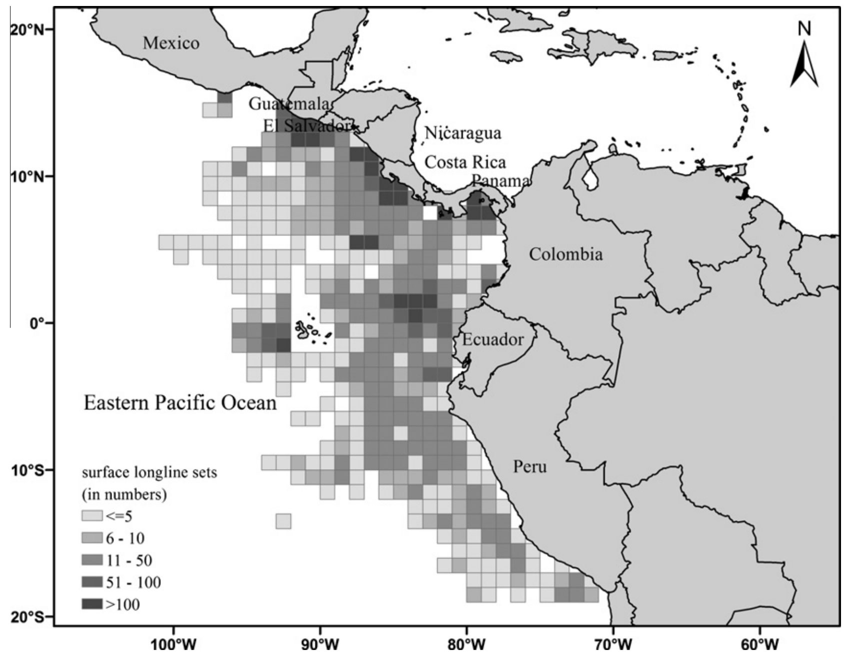

Fig. 1. Distribution of fishing effort (number of sets) observed by the program between 2004 and 2010 in 1° × 1° grids.

For Ecuador we analyzed the differences in hooking rates between J-style hooks (pooled Nos. 4 and 5) vs. circle hooks, 14/0 and 15/0, in the mahi-mahi fishery and tuna hooks (pooled Nos. 38 and 40) vs. 16/0 circle hooks in the TBS fishery; for Panama we compared hooking rates between tuna hooks (No. 8/0) vs. circle hooks 16/0 in the TBS fishery; and for Costa Rica we compared tuna hooks (pooled Nos. 34 and 36) vs. circle hooks 16/0 and 18/0 in the TBS fishery, and J-style hooks (pooled Nos. 2 and 3) vs. 16/0 circle hooks in the mahi-mahi fishery. In some instances, circle hooks of the same nominal size but with different features (e.g. with/without ring, offset/no-offset, among others) were used during the trails and pooled for the analysis (Table 1). Table 3 shows the sampling effort and numbers of fishes and sea turtles caught during the trials. Fishes and sea turtles captured in the experimental section of each set were identified to specie level in most cases.

J-style or tuna hooks and circle hooks were placed in an alternating pattern in the longlines to eliminate possible biases. Observers verified that baits were assigned to hooks at random, and that the baiter did not try to put larger baits on the larger circle hooks. When baits of two or more species were used in a set, the baiter was requested to put them on the hooks at random. In order to minimize the confounding effects of differences in gear configurations, as described earlier, the analysis of the surface fisheries data was separated by country and by longline category (mahi-mahi or TBS).

2.3. Statistical analysis

Differences in hooking rates of target and non-target species between J-style/tuna hooks and circle hooks were statistically tested for significance by a randomization test (Manly, 2007). This method was recommended and described in the report of the "Workshop on Turtle Bycatch Mitigation for Longline Fisheries: Experimental Design and Data Analysis" (IATTC, 2008). We used a similar approximation to Curran and Bigelow (2011) but the lack of balance in the number of hooks of both types (Table 3) forced us to compare hooking rates (CPUE in number of individuals per 1000 hooks) rather than catches, taking into account the differences in effort between hook types. The null hypothesis tested was no differences in catch rates between paired hook types. Data were randomized and re-sampled 99,999 times. Significance was determined comparing the observed mean difference with the mean differences from randomly allocating the observed values across the two samples (in this case the differences of mean CPUE in both treatments). Most individuals caught during the experiment were identified to the species level. However, prior to statistical analysis, it was thought convenient to simplify the testing by grouping some individuals into categories (genera or families).

Statistical analyses were carried out using the R software version 2.15.1 (R Development Core Team, 2012) using the 'sample' function (Ziefﬂer et al., 2011). For the analyses we considered the significance level at $p < 0.05$.

3. Results

A total of 1208 sea turtles were recorded during the 3126 sets, 746 individuals on J-style and tuna hooks and 462 on circle hooks (Table 3). Ninety-nine percent ($n = 1196$) of the sea turtles caught were encountered and released alive. The most frequently caught species was by far the olive ridley sea turtle (71% of all turtles caught, $n = 852$) followed by the black/green sea turtle (17%, $n = 207$).

3.1. Comparison of CPUE (hooking rates) by country and fishery

3.1.1. Ecuador TBS comparison

Sea turtle hooking rates were reduced by over 50% by using 16/0 circle hooks compared with the traditional tuna hooks used in this fishery and this difference was highly significant (Table 4). For the majority of the fish species caught, circle hooks did not affect their hooking rates except for an increase in the catch of some of the main target species, particularly significant for the yellowfin tunas and wahoo, *Acanthocybium solandri*. There were also significant increases in catch rates of blue shark, *Prionace glauca*, silky shark, *Carcharhinus falciformis* and pelagic stingray, *Pteroplatytrygon violacea* with 16/0 circle hooks (Table 4).

Table 3
Summary of sampling effort (in number of sets and hooks) and captures (sea turtles, and fishes) recorded in the experiments used to compare hooking rates in the countries analyzed (Ecuador, Panama and Costa Rica).

Country	Longline category	Hooks compared[a]		Sampling effort			Catch number			
				Number of sets	Hooks deployed		Fishes		Sea turtles	
		J-hook	Circle		J-hook	Circle	J-hook	Circle	J-hook	Circle
Ecuador	TBS	Tuna (Nos. 38, 40)	16/0	2068	178,732	177,942	3489	4401	223	119
	Mahi mahi	J-style (Nos. 4,5)	14/0	131	11,195	11,174	1732	1189	25	14
	Mahi mahi	J-style (Nos. 4,5)	15/0	130	12,197	11,930	1789	1084	24	19
Panama	TBS	Tuna (No. 8/0)	16/0	110	40,890	34,619	750	736	92	32
Costa Rica	TBS	Tuna (Nos. 34, 36)	16/0	248	69,040	65,603	1282	1108	105	96
	TBS	Tuna (Nos. 34, 36)	18/0	122	38,207	36,834	947	1351	50	13
	Mahi mahi	J-style (Nos. 2, 3)	16/0	317	77,199	74,474	2242	2506	227	169
Total				3126	328,523	401,839	12,231	12,375	746	462

[a] Hook size refers to local names used by fishermen in each country.

Table 4
Results of the randomization tests for the species or groups of species caught in the experiment tuna-hook vs. C16/0 in the TBS fishery from Ecuador. Catch per unit of effort (CPUE) are in individuals per thousand hooks. Dash lines mean that no statistical analysis was performed.

Specie or group of species	Catch number		CPUE		*p*
	Tuna hook	Circle hook 16/0	Tuna hook	Circle hook 16/0	
Thunnus albacares	162	298	1.21	2.23	**<0.001**
Thunnus obesus	101	154	0.75	1.15	0.177
Xiphias gladius	210	223	1.57	1.67	0.814
Coryphaena hippurus	529	529	3.94	3.97	0.917
Katsuwonus pelamis	13	30	0.1	0.22	0.21
Istiophorus platypterus	55	62	0.41	0.46	0.628
Istiompax indica	58	65	0.43	0.49	0.299
Makaira nigricans	261	273	1.95	2.05	0.464
Kajikia audax	117	116	0.87	0.87	0.536
Acanthocybium solandri	18	47	0.13	0.35	**0.003**
Lepidocybium flavobrunneum	17	22	0.13	0.16	0.722
Prionace glauca	287	396	2.14	2.97	**<0.001**
Isurus oxyrinchus	16	18	0.12	0.13	0.237
Alopias pelagicus	592	648	4.41	4.86	0.223
Alopidae[a]	20	33	0.15	0.25	0.138
Carcharhinus falciformis	117	171	0.87	1.28	**0.019**
Carcharhinidae[a]	22	19	0.16	0.14	0.218
Sphyrnidae[a]	34	50	0.25	0.37	0.241
Dasyatidae[a]	33	30	0.25	0.22	0.983
Pteroplatytrygon violacea	5	20	0.04	0.15	**<0.001**
All fishes	2667	3204	20.09	24.37	**0.001**
Caretta caretta	0	1	0.00	0.01	–
Chelonia mydas	24	16	0.18	0.12	**0.021**
Dermochelys coriacea	0	3	0.00	0.02	–
Eretmochelys imbricata	1	0	0.01	0.00	–
Lepidochelys olivacea	155	63	1.16	0.47	**<0.001**
All sea turtles	180	83	1.34	0.62	**<0.001**

Note: Bold values correspond to p-values that are statistically significant.
[a] Grouped into families by low numbers or unidentified species.

3.1.2. Ecuador mahi-mahi comparisons

Both sizes of circle hooks used, 15/0 and 14/0, showed a significant reduction in hooking rates of the main, and almost only, target species (mahi-mahi) compared with J-style hooks (Table 5). Sea turtles showed a significant decline in hooking rates for the pooled species group with 14/0 circle hooks. However, the reduction by 15/0 circle hook was not significant (Table 5).

3.1.3. Panama TBS comparison

In the comparison between tuna hooks and 16/0 circle hooks, there were significant reductions in hooking rates for the pooled sea turtles (close to 50%) and for the olive ridley with circle hooks. None of the fish species caught showed significant differences between hook types (Table 6).

3.1.4. Costa Rica TBS comparisons

For the comparisons between tuna hooks and 16/0 circle hooks, the results showed a significant decrease in the hooking rates of swordfish and blue shark with circle hooks. The observed reductions in hooking rates for some tuna species (yellowfin, bigeye, *Thunnus obesus* and skipjack, *Katsuwonus pelamis*) with circle hooks were not significant (Table 7). On the other hand, significant increases in the catch rates of sailfish, *Istiophorus platypterus* and hammerhead shark, *Sphyrna zygaena* with circle hooks were observed. The reduction in sea turtles hooking rates by 16/0 circle hook was not significant, tuna hooks and 16/0 circle hooks caught almost the same number of sea turtles during the experiments (Table 7).

Large circle hooks 18/0 showed a significant reduction in sea turtle hooking rates compared to the control tuna hooks (close to 75% down), with reductions for all species of turtles caught (Table 7). The fish hooking rates in 18/0 circle hooks were significantly higher than those in J-style hooks for swordfish, silky shark and hammerhead shark. Of these, the silky shark is the most important in numbers. Others target species, like yellowfin tuna, show an increase in the hooking rates but it was not statistically significant (Table 7).

Table 5
Results of randomization tests for species or groups of species caught in the experiment J vs. C15/0 and J vs. C14/0 in the mahi-mahi fishery from Ecuador. Catch per unit of effort (CPUE) are in individuals per thousand hooks. Dash lines mean that no statistical analysis was performed.

Species or group of species	Catch number		CPUE		*p*	Catch number		CPUE		*p*
	J-style hook	Circle hook 15/0	J-style hook	Circle hook 15/0		J-style hook	Circle hook 14/0	J-style hook	Circle hook 14/0	
Coryphaena hippurus	1758	1030	144.13	86.34	**<0.001**	1701	1139	151.94	101.93	**<0.001**
Other bony fishes[a]	10	30	0.82	2.51	**0.001**	10	35	0.89	3.13	**<0.001**
Sharks[b]	7	14	0.57	1.17	0.261	7	11	0.63	0.98	0.446
Dasyatidae	14	10	1.15	0.84	0.261	14	4	1.25	0.36	**0.005**
All fishes	1789	1084	146.68	90.86	**<0.001**	1732	1189	154.71	106.41	**<0.001**
Caretta caretta	0	0	0.00	0.00	–	1	0	0.09	0.00	–
Chelonia mydas	5	4	0.41	0.34	0.708	5	0	0.45	0.00	–
Eretmochelys imbricata	6	1	0.49	0.08	**0.006**	6	5	0.54	0.45	0.731
Lepidochelys olivacea	13	14	1.07	1.17	0.794	13	9	1.16	0.81	0.246
All sea turtles	24	19	1.97	1.59	0.481	25	14	2.23	1.25	**0.014**

Note: Bold values correspond to p-values that are statistically significant.
[a] Includes: *Acanthocybium solandri, Katsuwonus pelamis, Thunnus albacares, T. obesus and Kajikia audax.*
[b] Includes: *Isurus oxyrinchus, Prionace glauca and Sphyrna zygaena.*

Table 6
Results of randomization tests for species or groups of species caught in the experiment tuna hook vs. C16/0 in the TBS fishery from Panama. Catch per unit of effort (CPUE) are in individuals per thousand hooks.

Specie or group of species	Catch number		CPUE		*p*
	Tuna hook	Circle hook 16/0	Tuna hook	Circle hook 16/0	
Thunnus albacares	248	275	6.15	8.06	0.719
Coryphaena hippurus	122	104	3.03	3.05	0.135
Billfishes[a]	33	41	0.82	1.20	0.75
Little tunas[b]	101	92	2.51	2.70	0.627
Other bony fishes[c]	22	19	0.55	0.56	0.659
Alopidae	90	70	2.23	2.05	0.094
Sphyrnidae	44	38	1.09	1.11	0.446
Carcharhinidae	34	51	0.84	1.49	0.999
All fishes	694	690	17.36	20.33	0.404
Chelonia mydas	10	2	0.25	0.06	0.384
Lepidochelys olivacea	72	29	1.79	0.85	**<0.001**
All sea turtles	82	31	2.03	0.91	**<0.001**

Note: Bold values correspond to p-values that are statistically significant.
[a] Includes: *Istiophorus platypterus*, *Istiompax indica*, *Makaira nigricans* and *Tetrapturus* sp.
[b] Includes: *Euthynnus lineatus*, *Katsuwonus pelamis*, *Sarda chiliensis chiliensis* and *S. orientalis*.
[c] Includes mainly *Caranx* sp.

3.1.5. Costa Rica mahi-mahi comparison

There was a reduction of almost 25% in the pooled sea turtle hooking rates, and also for the olive ridley sea turtle with 16/0 circle hooks in relation to J-style hooks. The hooking rates on circle hooks, for all bony fishes and sharks combined, showed a small significant increase but the main target species of the fishery (mahi-mahi) showed no significant changes. Also, a significant increase with 16/0 circle hooks was detected for the silky shark (Table 8).

4. Discussion

There are only a few studies comparing traditional J and tuna hooks vs. circle hooks in artisanal or small-scale longline fisheries (i.e. Cambiè et al., 2012; Rodríguez-Valencia et al., 2008). Therefore, it is difficult to compare the results with others in similar fishing conditions. In the EPO region most of the studies have been focused on the mahi-mahi fishery looking at differences in hooking location and catch rates of target and non-target species but only between circle hooks (i.e. different sizes and offsets) (Swimmer et al., 2010; Whoriskey et al., 2011). Thus, the results presented in this paper are essential to evaluate circle hooks performance in the EPO and to contribute to the knowledge of circle hooks performance in artisanal longline fisheries worldwide.

In agreement with other studies in the EPO (Swimmer et al., 2006, 2010; Whoriskey et al., 2011), the olive ridley was the sea turtle most commonly hooked followed by the black/green sea turtle. The results showed that most of these individuals reach the vessel alive. This is because hooks are set near the surface and sea turtles hooked can reach the surface to breathe. This, in conjunction with properly handling techniques, allows fishers to release them alive. Although, post-release mortality is not known (Parga, 2012), some studies are encouraging, suggesting that sea turtles lightly hooked and handled correctly survive after interactions with shallow-set longlines (Swimmer et al., 2006).

Differences in hooking rates between circle and J-hooks for target and non-target species were not consistent for all fisheries and countries analyzed. The results obtained in the present study support the findings of some review studies that suggested that the performance of circle hooks depended on a variety of factors such as hook shapes and sizes compared, species involved, fishing technique used, region, among many others (Gilman et al., 2006; Read, 2007; Serafy et al., 2012).

Table 7
Results of randomization tests for species or groups of species caught in the experiment tuna hook vs. C16/0 and tuna hook vs. C18/0 in the TBS fishery from Costa Rica. Catch per unit of effort (CPUE) are in individuals per thousand hooks. Dash lines mean that no statistical analysis was performed.

Specie or group of species	Catch number		CPUE		*p*	Catch number		CPUE		*p*
	J-style hook	Circle hook 16/0	J-style hook	Circle hook 16/0		J-style hook	Circle hook 18/0	J-style hook	Circle hook 18/0	
Thunnus albacares	149	105	2.16	1.60	0.111	16	25	0.42	0.68	0.308
Thunnus obesus	60	53	0.87	0.81	0.138	0	0	0	0	–
Katsuwonus pelamis	25	13	0.36	0.20	0.076	0	0	0	0	–
Coryphaena hippurus	486	431	7.04	6.57	0.208	130	111	3.4	3.01	0.806
Xiphias gladius	181	83	2.62	1.27	**<0.001**	20	38	0.52	1.03	**0.037**
Istiophorus platypterus	39	65	0.56	0.99	**0.030**	40	45	1.05	1.22	0.869
Other billfishes[a]	57	57	0.83	0.87	0.466	29	28	0.76	0.76	0.993
Prionace glauca	41	25	0.59	0.38	**0.013**	53	81	1.39	2.2	0.126
Carcharhinus falciformis	185	196	2.68	2.99	0.803	594	934	15.55	25.36	**0.002**
Alopidae	21	28	0.30	0.43	0.405	30	32	0.79	0.87	0.694
Sphyrnidae	8	16	0.12	0.24	**0.009**	27	34	0.71	0.92	**0.036**
All fishes	1252	1072	18.57	16.89	**0.046**	947	1351	24.79	36.68	**0.001**
Chelonia mydas	15	15	0.22	0.23	0.798	19	1	0.5	0.03	**<0.001**
Eretmochelys imbricata	1	1	0.01	0.02	–	1	0	0.03	0	–
Lepidochelys olivacea	78	73	1.13	1.11	0.709	30	12	0.79	0.33	**0.012**
Testudinata	11	7	0.16	0.11	–	0	0	0	0	–
All sea turtles	105	96	1.52	1.46	0.875	50	13	1.31	0.35	**<0.001**

Note: Bold values correspond to p-values that are statistically significant.
[a] Includes: *Makaira nigricans*, *Istiompax indica*, *Kajikia audax*, *T. angustirostris* and *Tetrapturus* sp.

4.1. TBS fisheries

Encouraging results were observed in the TBS fishery in Ecuador, Panama and Costa Rica however the results varied according to the country and species considered. Sea turtle hooking rates were reduced by over 50% using 16/0 circle hooks compared with the traditional tuna-hooks used in the longline fisheries from Ecuador and Panama. Bolten and Bjorndal (2005) also found a significant difference in the catch rate for loggerheads sea turtles between these hooks types. However, this reduction was not observed in the TBS fishery from Costa Rica where the larger circle hook (18/0) appeared to be more effective in the reduction of sea turtle bycatch than the smaller one (16/0). It is difficult to explain why 16/0 circle hooks reduce the sea turtle bycatch in Ecuador and Panama and not in Costa Rica. These differences may be a product of different fishing techniques, hooks materials, bait type, region (Serafy et al., 2012), nesting season, turtle sizes or abundance.

Regarding target species such as yellowfin tuna, an increase in the observed catch rates with 16/0 circle hooks was observed in Ecuador, but in the Panamanian and Costa Rican TBS fisheries they remained constant. Kerstetter and Graves (2006) comparing J-hooks with 16/0 circle hooks in the Atlantic also found that circle hooks generally increased yellowfin tuna catches. In addition, others studies comparing J-hooks with 17/0 and 18/0 circle hooks also found an increase in the catches of tuna species (Curran and Bigelow, 2011; Domingo et al., 2012; Sales et al., 2010). However, effectiveness of circle hooks on target species is difficult to compare due to differences in hook types, sizes, and fisheries strategies used among studies (Curran and Bigelow, 2011).

Kerstetter and Graves (2006) and Coelho et al. (2012) found a significant decrease in the catch rates of swordfish using 16/0 and 17/0 circle hooks respectively as we observed in the Costa Rican TBS fishery with 16/0 circle hooks. Nonetheless, increases in swordfish catch rates were observed using 18/0 circle hooks in

Table 8
Results of randomization tests for species or groups of species caught in the experiment J vs. C16/0 in the mahi-mahi fishery from Costa Rica. Catch per unit of effort (CPUE) are in individuals per thousand hooks. Dash lines mean that no statistical analysis was performed.

Specie or group of species	Catch number		CPUE		*p*
	J-style hook	Circle hook 16/0	J-style hook	Circle hook 16/0	
Coryphaena hippurus	1904	2075	24.66	27.86	0.129
Istiophorus platypterus	151	163	1.96	2.19	0.134
Carcharhinus falciformis	59	84	0.76	1.13	**0.039**
Alopias spp.	43	59	0.56	0.79	0.257
Other billfishes[a]	46	55	0.60	0.74	0.097
All fishes	2203	2436	29.04	33.65	**0.033**
Chelonia mydas	45	46	0.58	0.62	0.976
Eretmochelys imbricata	2	6	0.03	0.08	–
Lepidochelys olivacea	179	112	2.32	1.50	**0.003**
Testudinata	1	5	0.01	0.07	–
All sea turtles	227	169	2.94	2.27	**0.020**

Note: Bold values correspond to p-values that are statistically significant.
[a] Includes: *Xiphias gladius*, *Makaira nigricans*, *Istiompax indica*, *Kajikia audax* and *T. angustirostris.*

Table 9
Matrix of impacts of the hook replacement on sea turtles and (A) target species and (B) other bycatch species.

(A)			
Sea turtles vs. target	Target catch higher	Target catch same	Target catch lower
Sea turtle bycatch higher	Ineffective	Ineffective	Ineffective
Sea turtle bycatch same	Ineffective/accepted by fishers	Null effect	Ineffective/rejected by fishers
Sea turtle bycatch lower	Depends on target stock status	Effective/look other bycatches	Rejected by fishers
(B)			
Sea turtle vs. other bycatch	Other bycatch higher	Other bycatch same	Other bycatch lower
Sea turtle bycatch higher	Ineffective	Ineffective	Ineffective
Sea turtle bycatch same	Ineffective	Null effect	Ineffective/depends
Sea turtle bycatch lower	Depends on conservation status of both bycatches	Effective	Effective

the same fishery. Unfortunately, the number of swordfish caught in this experiment was very low to draw definitive conclusions.

In addition, the catch rates of other commercially important species, i.e. blue and silky sharks, increased significantly with circle hooks in Ecuador and Costa Rica. This is consistent with the increase in the sharks catch rates with circle hooks founded in others parts of the world (Domingo et al., 2012; Sales et al., 2010; Ward et al., 2009; Watson et al., 2005). The silky sharks comprise a significant portion of the catches in TBS fisheries in the EPO and because this species is considered Near Threatened globally (IUCN, 2012) and Vulnerable in the Eastern Central and Southeast Pacific (Kyne et al., 2012), several management actions are under way at the National (e.g. Plans of Action for Sharks) and at the International levels, through the Tuna Regional Fisheries management Organizations.

Several studies suggest that at-vessel shark mortality decreases significantly using circle hooks because these hooks were more frequently lodged in the mouth or jaw rather than internally (Afonso et al., 2011; Carruthers et al., 2009; Godin et al., 2012). Thus, the use of circle hooks, combined with better handling and hook removal techniques could result in successful releases of sharks in the fisheries where they are bycatches. However, solid management measures are needed in the fisheries that target sharks as a principal or secondary target species.

4.2. Mahi-mahi fisheries

The mahi-mahi fisheries from Ecuador and Costa Rica are quite completely dominated by mahi-mahi, and the captures of other fish species are very minor. In the Ecuadorian fishery, hooking rates of target species with 15/0 and 14/0 circle hooks were significantly lower than those with J-hooks and, although the results are encouraging for sea turtles (significant reductions with 14/0 hooks), it will be difficult to persuade fishers to adopt the new hook due to such losses in production. Similar results were observed previously by Largacha et al. (2005) for the same fishery and by Rodríguez-Valencia et al. (2008) for the Mexican mahi-mahi fishery comparing non-offset 14/0, 16/0 and 18/0 circle hooks.

A possible reason of the observed reduction in the catch rates of mahi-mahi with 14/0 and 15/0 circle hooks in Ecuador may be the differences in fishing efficiency and size-selectivity between traditional J-hook and circle hooks. Hook width of 15/0 and 14/0 circle hooks were larger than those of Nos. 4 and 5 J-hooks. Some studies on size selectivity of longline hooks showed that larger hooks were less effective for smaller fishes (Erzini et al., 1996; Yamahita et al., 2009).

The significant reduction in sea turtle hooking rates with 14/0 circle hooks compared with the non-significant reduction with 15/0 circle hooks in Ecuador could be a consequence of the low sample sizes in both comparisons (Table 5) since it is difficult to explain how a larger circle hook caught more sea turtles than the smaller one. In addition in the Costa Rican mahi-mahi fishery, with the 16/0 circle hook, there is a reduction of almost 25% in sea turtle hooking rates. Future analysis should consider turtle sizes in relation to hook sizes to find if a confounding effect is present.

The olive ridley hooking rates observed in the Costa Rican mahi-mahi fishery in this study (1.5 turtles per 1000 hooks with 16/0 circle hooks) are 6–12 times lower than those reported in recent studies of 9.05 turtles per 1000 hooks with 14–16/0 circle hooks (Whoriskey et al., 2011) and 19 turtles per 1000 hooks with 14/0 circle hooks (Swimmer et al., 2010) in the same fishery. The present study has larger sample sizes, and comes from a wider geographical area suggesting that a small sample obtained in the vicinity of the nesting beaches, and during the period when a high density of turtles is coming to nest could bias the results (Swimmer et al., 2010).

4.3. Assessing the impact of hook exchanges

The mitigation actions that can be taken to reduce bycatch can be specific (e.g. tori lines only affect seabird bycatches in longlines) or generic (affecting the selectivity of the gear with respect to all species captured) such as the change from J-hooks to circle hooks examined in this paper. Thus, a complete evaluation of the ecological impact of the replacement of J-style or tuna hooks by circle hooks requires a holistic approach that considers the changes in selectivity for both fish and sea turtle species, and the condition of the stocks impacted (threatened and/or overfished.). A way to summarize the options available is presented in the Table 9A and B. For example, in the artisanal longline fisheries in the EPO we can found, among target species, sharks that are of special conservation concern (i.e. silky shark) or others species, such as mahi-mahi, which are categorized as least concern (Appendix; IUCN, 2012).

In some cases, like the Costa Rica TBS fishery with 18/0 circle hooks or in mahi-mahi fishery with 16/0, the reduction in sea turtle hooking rates may be accompanied by increases in catch rates of other target species such as silky sharks that are of conservation concern ("Depend on target stock status" in Table 9A). Thus, it is necessary to compare the status of the sea turtles involved (e.g. olive ridley are quite numerous, and are increasing in abundance) (Chaloupka et al., 2004), with the status of the sharks (e.g. the silky shark populations probably have been decreasing) (Bonfil et al., 2009) to evaluate the implementation of circle hooks. In the case of sharks, the mortality suffered in longline fisheries is an issue related to the overall management of these fisheries where they are target, and many different factors (other than hook type) that were not accounted for in this analysis. Nonetheless, circle hooks may facilitate the release of the sharks, or their survival after release, and in this way they may compensate or exceed the negative impacts of the higher catches.

A desirable outcome is that circle hooks reduce sea turtle bycatch, with no impact on the catch rates of the target species, and therefore there is no negative impact, even in the cases where overfishing is occurring (Table 9A). This one may be the best scenario in some situations. Examples of this type of outcome are the results with 16/0 circle hooks in the TBS fishery from Panama where there were no negative impacts on target species or in other bycatch species (Table 9B).

On the other hand, the mahi-mahi fishery from Ecuador with 14/0 circle hooks showed a significant decline in sea turtle hooking rates, but also a significant reduction in target catch rates, so the adoption of the hooks could be problematic ("Ineffective/Rejected by fishers" in Table 9A). Further research and others alternatives are needed to reach the best solution in this fishery.

In some cases, the results are very positive (e.g. Panama TBS fishery); in others they are not encouraging (e.g. Ecuadorian mahi-mahi fishery). When there is no reduction in sea turtle hooking rates, we are left with doubts on other beneficial effects of circle hooks. Will positive changes in turtles encountered dead at haulback and in the location of hooks be significant enough to justify the major logistical and managerial operation to replace all J-style hooks? This is further exacerbated when there are losses in target species hooking rates such as the cases of the use of 16/0 circle hook in the TBS fisheries from Costa Rica ("Ineffective" in Table 9A). Increases in catch rates, for fisheries where overfishing is not a problem may be a welcome way to improve production with less expenditure of energy and bait as occurred with 18/0 circle hooks in the TBS fishery from Costa Rica.

The different results observed in each fishery show that performing the analysis independently by country and fishery was the best approach. Results like those presented in this paper best support fishery/regionally-specific management approaches. In spite of the convenience of the one-size-fits-all approach, the ecological impacts of the change vary with the species, size composition of the catches, the status of the populations involved, among others. Thus a carefully thought out assessment of all the pros and cons needs to be made, instead of a blanket recommendation of adopting circle hooks in all fisheries.

Additionally, any recommendation on the use of circle hooks should consider their practical utility in each fishery and availability, accessibility and affordability in countries (Yokota et al., 2012). Meanwhile, measures to improve the handling of hooked turtles with the right use of instruments and techniques in regional and national fisheries longline can be taken to increase the survival of these species (Parga, 2012).

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Appendix A

Main species caught in the surface longline fisheries of the EPO and analyzed in this study with each IUCN red list status. LC = low concern, NT = near threatened, VU = vulnerable and DD = data deficient.

Species	Common name	Status IUCN
Tunas		
Thunnus albacares (Bonnaterre, 1788)	Yellowfin tuna	NT
Thunnus obesus (Lowe, 1839)	Bigeye tuna	VU
Katsuwonus pelamis (Linnaeus, 1758)	Skipjack tuna	LC
Euthynnus lineatus Kishinouye, 1920	Black skipjack	LC
Sarda orientalis (Temminck & Schlegel, 1844)	Striped Bonito	LC
Sarda chiliensis chiliensis (Cuvier, 1832)	Eastern Pacific bonito	[a]
Acanthocybium solandri (Cuvier, 1832)	Wahoo	LC
Billfishes		
Xiphias gladius Linnaeus, 1758	Swordfish	LC
Istiompax indica (Cuvier, 1832)	Black marlin	DD
Makaira nigricans Lacepède, 1802	Blue marlin	VU
Istiophorus platypterus (Shaw, 1792)	Indo-Pacific sailfish	LC
Kajikia audax (Philippi, 1887)	Striped marlin	NT
Tetrapturus angustirostris Tanaka, 1915	Shortbill spearfish	[a]
Others bony fishes		
Coryphaena hippurus Linnaeus, 1758	Common dolphinfish/Mahi-mahi	LC
Lepidocybium flavobrunneum (Smith, 1843)	Oilfish	[a]
Sharks		
Prionace glauca (Linnaeus, 1758)	Blue shark	NT
Isurus oxyrinchus Rafinesque, 1810	Shortfin mako	VU
Alopias pelagicus Nakamura, 1935	Pelagic thresher	VU
Alopias superciliosus Lowe, 1841	Bigeye thresher	VU
Carcharhinus falciformis (Müller & Henle, 1839)	Silky shark	NT
Sphyrna zygaena (Linnaeus, 1758)	Smooth hammerhead	VU
Rays		
Pteroplatytrygon violacea (Bonaparte, 1832)	Pelagic stingray	LC

[a] This taxon has not yet been assessed for the IUCN Red List.

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